PB91-197301

Use, Availability and Cost-Effectiveness of Asphalt Rubber in Texas

Texas Transportation Inst., College Station

Prepared for:

Federal Highway Administration, Austin, TX

Sep 90

U.S. Department of Commerce
National Technical Information Service
NTIS

TTI: 2-8-90-1902-1F

PB91-197301

TEXAS TRANSPORTATION INSTITUTE

USE, AVAILABILITY AND COST-EFFECTIVENESS OF ASPHALT RUBBER IN TEXAS

RESEARCH REPORT 1902-1F

COOPERATIVE RESEARCH PROGRAM

TEXAS TRANSPORTATION INSTITUTE
THE TEXAS A&M UNIVERSITY SYSTEM
COLLEGE STATION, TEXAS

STATE DEPARTMENT OF HIGHWAYS
AND PUBLIC TRANSPORTATION

REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA 22161

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2	3. Recipient's Catalog No.
TX-91/1902-1F	PB91-197301	

4. Title and Subtitle	5. Report Date
USE, AVAILABILITY AND COST-EFFECTIVENESS OF ASPHALT RUBBER IN TEXAS	September 1990
	6. Performing Organization Code

7. Author(s)	8. Performing Organization Report No.
Cindy K. Estakhri, Emmanuel G. Fernando, Joe W. Button and George R. Teetes	Research Report 1902-1F

9. Performing Organization Name and Address	10. Work Unit No.
Texas Transportation Institute The Texas A&M University System College Station, Texas 77843-3135	11. Contract or Grant No. Study No. 2-8-90-1902
	13. Type of Report and Period Covered Final - September 1989 September 1990
12. Sponsoring Agency Name and Address Texas State Department of Highways and Public Transportation; Transportation Planning Division P. O. Box 5051 Austin, Texas 78763	14. Sponsoring Agency Code

15. Supplementary Notes
Research performed for the State of Texas.

16. Abstract
A study was conducted for the Texas State Department of Highways and Public Transportation (SDHPT) by the Texas Transportation Institute (TTI) to address the following issues: (1) the current extent of usage of asphalt rubber by the Department, (2) the availability of crumb rubber produced from scrap tires and the availability of asphalt rubber in the State of Texas, and (3) the cost-effectiveness of asphalt rubber as compared to conventional paving materials based on existing information and on the experience of Department personnel.

Published information was canvassed, phone interview with knowledgeable Department personnel were conducted, and existing laboratory information was evaluated. The Texas SDHPT currently utilizes asphalt rubber in four different applications. They are listed below in descending order of their volume of asphalt rubber consumption: (1) chip seal or stress absorbing membrane (SAM) construction, (2) stress absorbing membrane interlayer (SAMI) construction, (3) crack and/or joint sealing, and (4) hot-mix asphalt concrete pavement construction (on a very limited experimental basis). These applications of asphalt rubber are described in detail in the body of this report. Appendix A contains descriptions of current and proposed innovative uses for scrap tires other than in asphalt pavements which could potentially consume all of the scrap tires produced in the United States.

17. Key Words	18. Distribution Statement
Asphalt rubber, scrap tires, crumb rubber, ground tire rubber, stress absorbing membrane(SAM), stress absorbing membrane interlayer(SAMI)	No restrictions. This document is available to the public through the National Technical Information Service 5285 Port Royal Road Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	108	

Form DOT F 1700.7 (8-69)

USE, AVAILABILITY AND COST-EFFECTIVENESS OF ASPHALT RUBBER IN TEXAS

Research Study No. 2-8-90-1902

by

Cindy K. Estakhri

Emmanuel G. Fernando

Joe W. Button

George R. Teetes

Sponsored by the

State Department of

Highways and Public Transportation

Texas Transportation Institute

Texas A&M University

College Station, Texas 77843

September, 1990

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
AREA				
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
MASS (weight)				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
VOLUME				
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

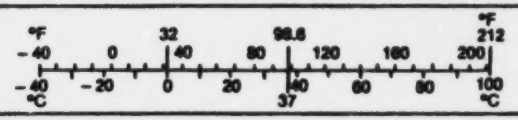
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
AREA				
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
MASS (weight)				
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
VOLUME				
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

TABLE OF CONTENTS

	Page
DEFINITIONS	v
SUMMARY AND CONCLUSIONS	1
INTRODUCTION	5
AVAILABILITY AND USE OF ASPHALT RUBBER	6
Waste Tire Availability	6
Asphalt Usage	6
Potential Tire Use in Asphalt Rubber	8
Use of Asphalt Rubber in Texas	12
ASPHALT-RUBBER CHIP SEALS (SAMs)	16
Experiences in Other States	16
Other Research in Texas	18
Texas Highway District Survey	20
Cost-Effectiveness	21
Summary	28
ASPHALT-RUBBER INTERLAYERS (SAMIs)	30
Experiences in Other states	30
SAMI Research in Texas	30
Survey of Texas Highway Districts	33
Cost-Effectiveness	35
Summary	36
ASPHALT-RUBBER CRACK SEALANTS	37
General	37
Survey of Texas Highway Departments	37
Cost-Effectiveness	38
Summary	38
RUBBER-MODIFIED ASPHALT CONCRETE MIXTURES	39
Experience in Other States	39
Experience in Texas	44
Performance and Cost Evaluation of Asphalt-Rubber Concrete Mixtures	45
Performance Evaluation of Asphalt-Rubber Concrete Mixtures	46
Cost-Effectiveness of Asphalt-Rubber Concrete Pavements	55
Summary	61
REFERENCES	63
APPENDIX A - OTHER USES OF SCRAP TIRES	66
APPENDIX B - BID PRICES FOR CHIP SEALS IN 1989	73
APPENDIX C - MATERIALS INFORMATION FOR EVALUATING ASPHALT-RUBBER	

DEFINITIONS

Asphalt - or asphalt cement is bituminous material from the refining of crude petroleum.

Asphalt Concrete - or hot mixed asphalt concrete is a mixture of approximately 5 percent asphalt and 95 percent aggregate used for highway pavement surfaces.

Aggregate - as the term is used in this report refers to rocks or stones of a uniform size or in a range of sizes from one of two sources: naturally occurring deposits or artificially or industrially prepared materials.

Asphalt Rubber - is a combination of asphalt and 18 to 22 percent reclaimed tire rubber resulting in an aggregate binder that exhibits greater recovery from deformation than conventional asphalts. Various petroleum distillates are sometimes added to reduce viscosity and enhance workability.

Chip Seal - is a single application of asphalt applied to a pavement surface followed immediately by a single layer of aggregate of a uniform size. A seal coat is applied to prevent intrusion of surface water into cracks, if any, and restore the texture or skid resistance of the pavement surface.

Flushing - sometimes called bleeding is a film of bituminous material on the pavement surface (usually in the wheelpaths) which creates a shiny, black appearance that may become quite sticky during hot weather. Flushing is caused by excessive amounts of asphalt cement in the mix and/or low air void contents.

SAM - is an abbreviation for stress-absorbing membrane. A SAM is an asphalt-rubber chip seal applied to the surface of a cracked pavement to seal the cracks and provide the added benefit of expansion and contraction with the pavement at the cracks to minimize the appearance of reflection cracking at the surface.

SAMI - is an abbreviation for stress-absorbing membrane interlayer. A SAMI is a thin interlayer placed between two pavement layers to dissipate tensile loads generated in a lower (usually) layer so that the loads do not produce reflective cracking in the uppermost pavement layer. A SAMI may consist of an asphal-rubber chip seal, fabric, fine unbound aggregate, or an open-graded asphalt-aggregate layer.

Reflective Cracking - is the migration of a subsurface cracking pattern in an old pavement into and through a subsequent asphalt-concrete overlay.

Pumping - results from the intrusion of surface water into the pavement base which softens the unbound base material to such an extent that traffic loadings will press down the pavement near a crack and pump out the fine aggregate in the form of an aqueous slurry.

SUMMARY AND CONCLUSIONS

A study was conducted for the Texas State Department of Highways and Public Transportation (SDHPT) by the Texas Transportation Institute (TTI) to address the following issues:

(1) the current extent of usage of asphalt rubber by the Department,

(2) the availability of crumb rubber produced from scrap tires and the availability of asphalt rubber in the State of Texas, and

(3) the cost-effectiveness of asphalt rubber as compared to conventional paving materials based on existing information and on the experience of Department personnel.

Published information was canvassed, phone interviews with knowledgeable Department personnel were conducted, and existing laboratory information was evaluated. The Texas SDHPT currently utilizes asphalt rubber in four different applications. They are listed below in descending order of their volume of asphalt rubber consumption:

(1) chip seal or stress-absorbing membrane (SAM) construction,

(2) stress-absorbing membrane interlayer (SAMI) construction,

(3) crack and/or joint sealing, and

(4) hot-mix asphalt concrete pavement construction (on a very limited experimental basis).

These applications of asphalt rubber are described in detail in the body of this report. Appendix A contains descriptions of current and proposed innovative uses for scrap tires other than in asphalt pavements which could potentially consume all of the scrap tires produced in the United States. The conclusions of this study are summarized below.

AVAILABILITY AND USE

1. Approximately 150 million scrap tires are currently stored in Texas and another 18 million are being discarded in the state each year. The scrap tires accumulated annually could be used to produce 108,000 tons of rubber suitable for use in asphalt-rubber products. The Texas SDHPT annually uses more than 1,000,000 tons of asphalt cement. If ten percent of this paving asphalt cement was routinely replaced with asphalt rubber, more

than 20 percent of the annual production of waste tires would be utilized. At the present, slightly more than one percent of this paving asphalt is replaced with asphalt rubber.

2. Only about 60 weight percent of a tire is consumed in producing asphalt rubber. Remaining products include primarily steel, fiber, and additional rubber.
3. The Texas SDHPT is currently using about 13,000 tons per year of asphalt rubber which accounts for approximately 430,000 scrap tires. However, most of the waste tires utilized in this material come from other states. The availability of crumb rubber in Texas is a rapidly changing issue. Findings indicate that next year seven to ten million tires may be recycled in plants in Texas.

ASPHALT-RUBBER CHIP SEALS

4. Asphalt-rubber chip seals have been constructed, at least on an experimental basis, in all parts of Texas. However, there are only five out of the 24 highway districts currently constructing asphalt-rubber chip seals with some regularity.
5. Utilization of asphalt rubber for chip seals in most highway districts in Texas has historically not been standard practice and 13 districts have no plans for increasing their use in the future. The primary reason cited for this is that asphalt rubber is too expensive and has not proven to be cost-effective in this application.
6. An asphalt-rubber chip seal costs two to three times more than a conventional chip seal. Proponents of asphalt-rubber chip seals claim they will last twice as long as a conventional chip seal.
7. There is not enough available information to accurately determine the cost-effectiveness of asphalt-rubber chip seals. However, an annualized cost analysis performed in this study revealed that an asphalt-rubber chip seal would have to last three times longer than a conventional asphalt chip seal in order to have an equivalent annual cost.
8. Districts in Texas which are experienced with asphalt-rubber chip seals do not usually construct them on a pavement where a conventional chip seal is a viable option. Asphalt-rubber chip seals are used successfully as a rehabilitative measure rather than preventive measure and they are often

placed on high-traffic volume roads. Therefore, a more valid comparison for asphalt-rubber chip seals might be with a thin overlay or multiple chip seal, in which case, the asphalt rubber is much more likely to be cost-effective.

ASPHALT-RUBBER INTERLAYERS (SAMIs)

9. Only six Texas highway districts have built stress-absorbing membrane interlayers (SAMI). Opinions of Department personnel regarding asphalt-rubber interlayers are much more favorable than those regarding asphalt-rubber chip seals. Most of the districts that have installed SAMI's believe they are effective in delaying reflective cracking. Some also believe SAMI's will reduce intrusion of surface water and pumping even after cracking occurs in the surface layer.
10. An asphalt-rubber SAMI may provide cost-effective improvements in performance of hot-mixed asphalt concrete overlays. Based on an annualized cost analysis performed in this study, an asphalt-rubber interlayer would need to last approximately 50 percent longer than an overlay constructed without an interlayer in order to be cost-effective.

ASPHALT-RUBBER CRACK SEALANTS

11. Asphalt-rubber crack sealant, which contains 20 percent ground tire rubber, is essentially the only crack sealant used by the Texas SDHPT. The Texas SDHPT uses approximately 3.5 million pounds of crack sealant annually.
12. Asphalt-rubber crack sealant is considered by all personnel interviewed in highway districts to be the best product available for sealing cracks in asphalt concrete and portland cement concrete pavements.

ASPHALT-RUBBER HOT MIX

13. Asphalt rubber has been used on a very limited basis in Texas for construction of hot mixed asphalt concrete (HMAC). The use of crumb rubber in HMAC is gradually gaining popularity across the United States; however, the technology is still somewhat in an experimental stage of development.
14. Results indicate that fatigue performance of asphalt concrete mixtures is

significantly improved with the addition of ground rubber. Thus, in areas where fatigue cracking is anticipated to be the primary mode of pavement distress, asphalt rubber may be a cost-effective alternative, and thus should be considered in the selection of materials for pavement design and construction.

15. Compared with additive-modified mixtures, the expected performance of asphalt rubber, in terms of both fatigue cracking and rutting, needs to improve and the cost of asphalt rubber reduced in order for it to be more competitive with polymer additive-modified mixtures, in particular, Kraton, Elvax, and Novophalt. The major component of the in-place cost is the cost of the asphalt-rubber binder itself. This cost may range from 41 to 45 percent of the in-place cost, depending on the binder content.

GENERAL

16. The Texas SDHPT and/or the Texas Legislature should not "go overboard" in promoting the use of tire rubber in asphalt since the benefit-cost ratios are not sufficiently high for every application. Providing a bonus for using tire rubber in asphalt pavements will not solve the problem. Careful consideration should be given to future utilization of asphalt pavement layers treated with rubber. For example, aged asphalt rubber may not accommodate recycling as well as unmodified asphalt. Agencies currently promoting the use of tire rubber in asphalt may be forced to place additional controls on the recycling of this product. A solution to the problem will require more research and engineering to provide self-supporting, cost-effective uses for scrap tires. There may be more economically efficient ways to recycle tires in much greater volumes than in asphalt pavements.

INTRODUCTION

Texas Senate Bill 1516 became effective in September 1989 and gave the following mandate (among others) to the State Department of Highways and Public Transportation:

> (1) "If the State Department of Highways and Public Transportation uses rubberized asphalt paving, the Department shall use scrap tires converted to rubberized asphalt paving by a facility in this state if that paving material is available.
>
> (2) In comparing bids submitted for road construction that require paving, the Department may give a preference to bids the paving materials portion of which includes the use of rubberized asphalt paving made from scrap tires by a facility in this state if the cost of those materials does not exceed by more than 15 percent the bid cost of alternative paving materials for the same job."

In order to make rational decisions regarding materials selection based on comparative cost-effectiveness, the Department initiated the study described herein. The objective of this study is to provide the following information to the Department: (1) the cost-effectiveness of asphalt rubber as compared to more conventional paving materials based on existing information and on the experience of Department personnel, (2) the availability of asphalt rubber in Texas, and (3) the current extent of usage of asphalt rubber in Texas. To meet these objectives, an extensive review of pertinent literature was performed, phone interviews of cognizant Department personnel in each district were conducted and other individuals were contacted, and laboratory data on asphalt concrete was used with mathematical models to predict comparative pavement performance. Applications of asphalt rubber in chip seals sometimes called stress-absorbing membranes (SAM), stress-absorbing membrane interlayers (SAMI), crack fillers, and dense and open-graded hot-mixed asphalt concrete were addressed.

For this study, asphalt rubber is defined as a blend of 18 to 22 percent ground tire rubber by total weight of the blend. The blend is typically formulated at elevated temperatures to promote chemical and physical interaction of the two constituents. Various petroleum distillates are sometimes added to the blend to reduce viscosity and enhance workability.

AVAILABILITY AND USE OF ASPHALT RUBBER

Governmental agencies including state highway departments and municipal street divisions are under public pressure to utilize waste materials to the greatest extent possible. Without question, this is the direction our society must move. Utilization of our waste materials and by-products is logical, sensible, and many times cost-effective. Incentives are sometimes offered by federal and state legislative bodies to promote the use of waste products.

WASTE TIRE AVAILABILITY

According to industry figures, there are as many as 2 billion scrap tires currently on the ground in the United States, with approximately 240 million tires being discarded in the United States each year (1). Of these, 200,000,000 are passenger car tires and 40,000,000 are truck tires(2).

It is estimated that Texas is accumulating scrap tires at a rate of 18 million annually and that there are approximately 150 million located at various storage sites around the state. These figures are based on the number of passenger cars and commercial vehicles registered in the state and an average tire life of four years.

A typical worn out passenger car tire weighs approximately 20 pounds and will provide about 60 percent rubber, 20 percent steel, and 20 percent fiber and other waste products (Figure 1). Based on these estimates, Texas drivers are generating each year the following potentially reusable materials: 108,000 tons of rubber, 36,000 tons of steel, and 36,000 tons of fiber. These estimates are conservative since they were computed using an average weight for passenger car tires and truck tires are much heavier.

ASPHALT USAGE

Approximately 32 million tons of asphalt were produced in the United States in 1987. Of this, about 27 million tons were used for paving, 4 million tons were used for roofing, and less than one million tons were used for other purposes. At 100 dollars per ton (a reasonable average cost), this translates into 2.7 billion dollars worth of asphalt cement per year for paving purposes. Approximately 90 percent of this was used in hot-mixed asphalt concrete (HMAC)

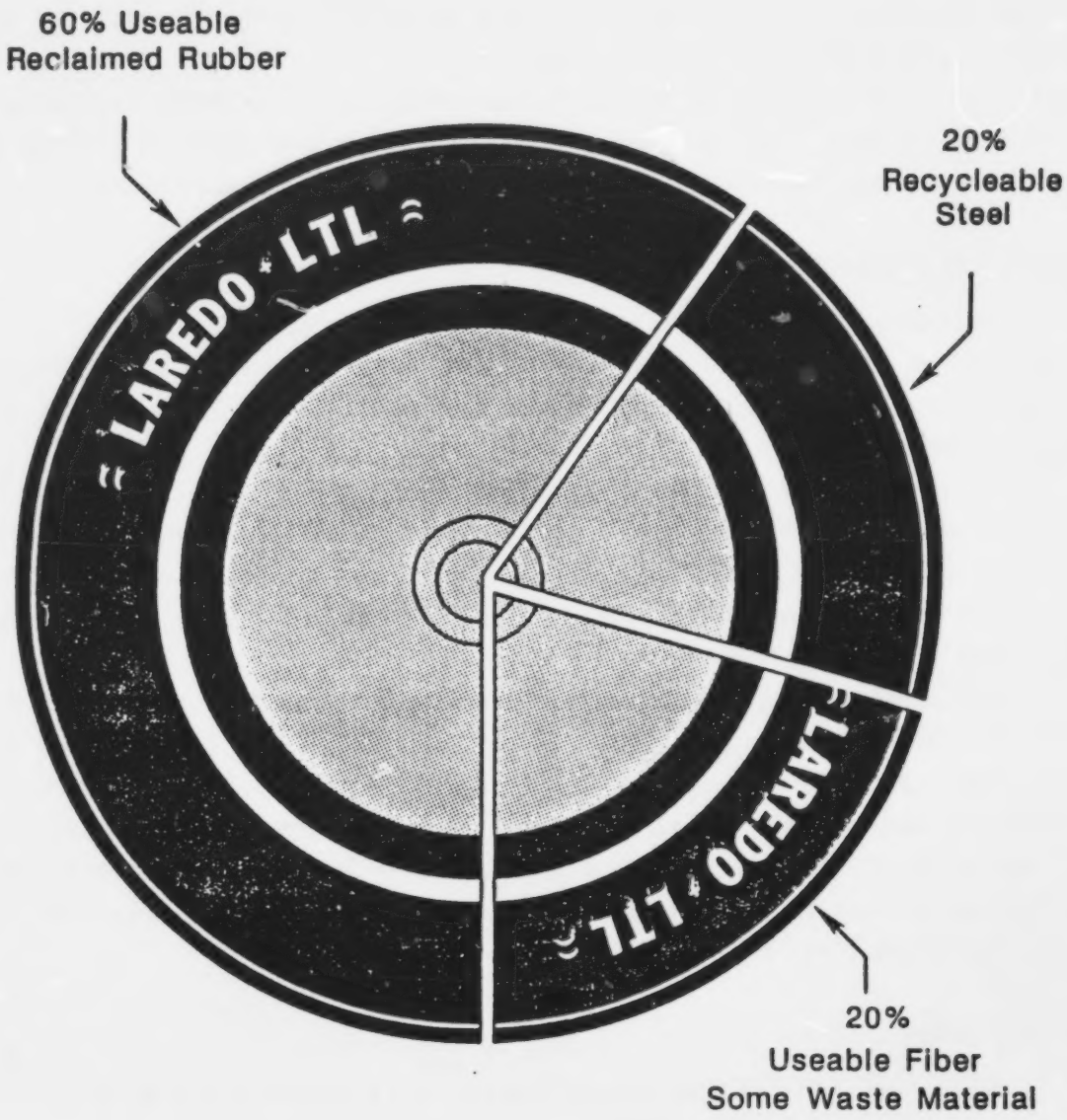


Figure 1. Potential Availability of Waste Tire Rubber in Texas.

and the other 10 percent was used for chip seals and surface treatments. The approximate quantity of HMAC produced in the U.S. was 500 million tons. At an average cost of 30 dollars per ton, it is estimated that more than 15 billion dollars were spent on HMAC during 1987. Although these values have varied somewhat, they are reasonably typical of the last eighteen years.

In Texas, about 20 million tons (or 0.6 billion dollars worth) of HMAC was produced in 1989 according to the Texas Hot-Mix Association. Just under one-half of this was purchased by the Texas State Department of Highways and Public Transportation (SDHPT). The remaining went to municipalities, airport authorities, and private buyers.

In fiscal year 1988, the Texas SDHPT used 1,100,000 tons of asphalt cement, 200,000 tons of emulsified asphalt, and 110,000 tons of cutback asphalt. Thus, a total of 1.4 million tons of asphalt products were used by the Texas SDHPT in 1988. These figures were obtained from the Materials and Tests Division (D-9) of the Texas SDHPT. (FY89 figures were unavailable at this writing.) Percentages of the various types of asphalt products that were used are depicted in Figure 2. A breakdown, by highway district, of the types of asphalt paving items produced or applied in Texas is given in Table 1.

POTENTIAL TIRE USE IN ASPHALT RUBBER

If 10 percent of the paving asphalt cement used annually by the State SDHPT was routinely replaced with asphalt rubber (using Texas tires), this would result in partial recycling of more than one-fifth of all the scrap tires accumulated annually in the state (Figure 3). Recall that only 60 percent of a tire is used in producing asphalt rubber. Therefore, the remaining 40 percent must be either disposed of or used in some other recycling process (Figure 1). Appendix A provides a brief update of the technology regarding recycling scrap tires in processes other than asphalt rubber.

In the past few years, most of the asphalt rubber paving material supplied to Texas has been furnished by Cox Paving Company of Blanco, Texas and International Surfacing, Inc. of Chandler, Arizona. Based on information from these suppliers, it is estimated that currently the Texas SDHPT is using 12,000 to 14,000 tons of asphalt rubber per year in paving operations. Another 1200 tons are used as asphalt-rubber crack sealant. Assuming that 20 percent tire

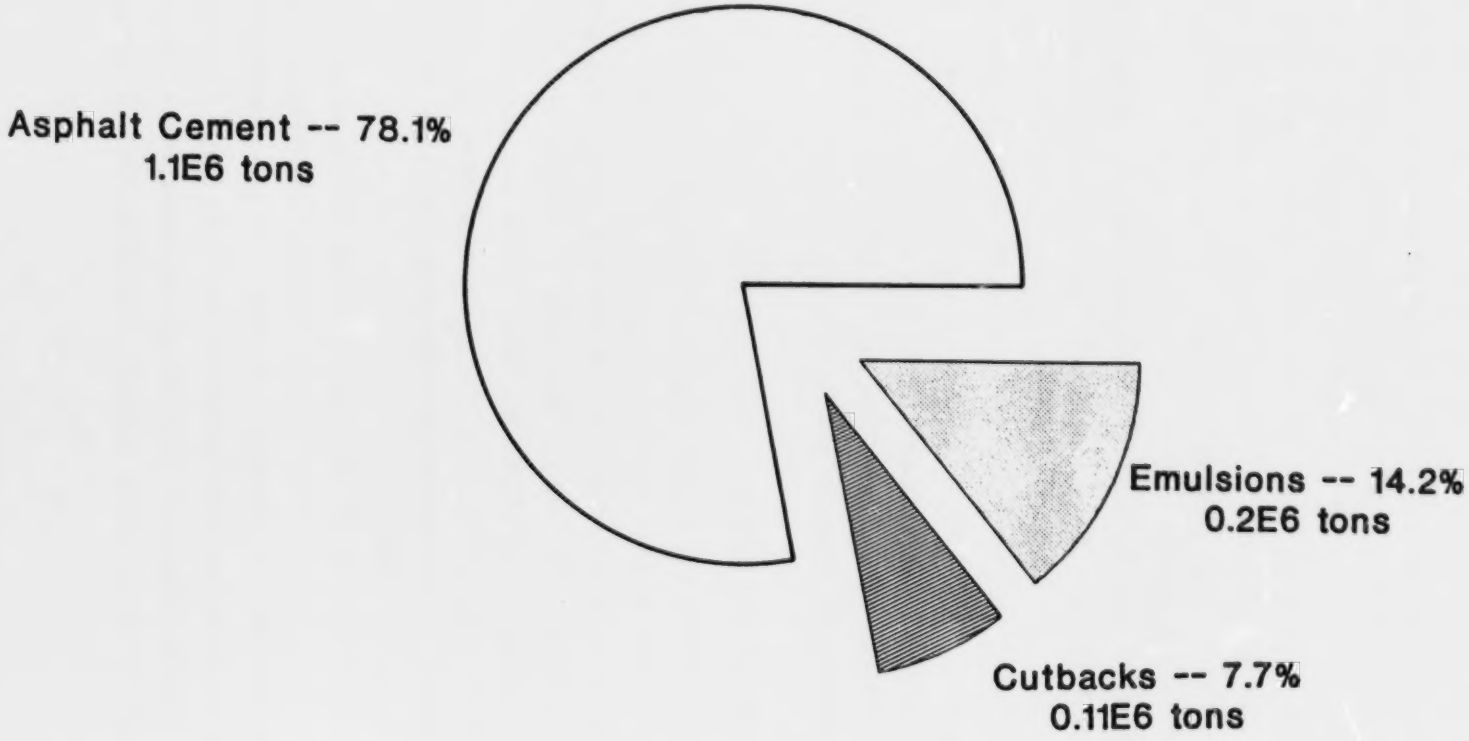


Figure 2. Approximate Quantity and Percentage of Each Type of Asphalt Product Purchased by the SDHPT in FY 1988.

Table 1. Asphalt Product Usage by District in Texas

District	Chip Seals[1] (Lane Miles)	Hot-Mix Asphalt Concrete[2] (Tons)	Asphalt-Rubber Crack Sealant[3] (LBS)
1	1,000	72,719	200,000
2	270	435,307	100
3	670	109,234	240,120
4	700	208,379	80,000
5	900	448,098	130,000
6	800	43,902	50,000
7	1,000	107,186	20,000
8	800	108,984	280,000
9	400	151,225	20,000
10	800	281,005	100,000
11	451	213,072	0
12	422	1,207,263	0
13	700	376,618	250,000
14	250	569,224	919,140
15	800	1,018,586	650,000
16	600	363,372	80,000
17	260	260,052	292,000
18	572	1,019,806	25,000
19	600	162,418	0
20	700	142,440	0
21	200	558,164	0
23	800	61,974	0
24	400	39,669	0
25	400	177,841	160,000
TOTAL	14,495 LM	8,136,538 Tons	3,496,360 LBS

[1] Estimates of 1990 seal coat programs determined from statewide district survey.
[2] 1989 tonnages as reported by the Texas Hot-Mix Association.
[3] As released by Texas SDHPT purchasing department for 1989. Note that this was the amount approved for purchase. It is estimated that approximately 70 percent of this was actually purchased, or 2,500,000 pounds.

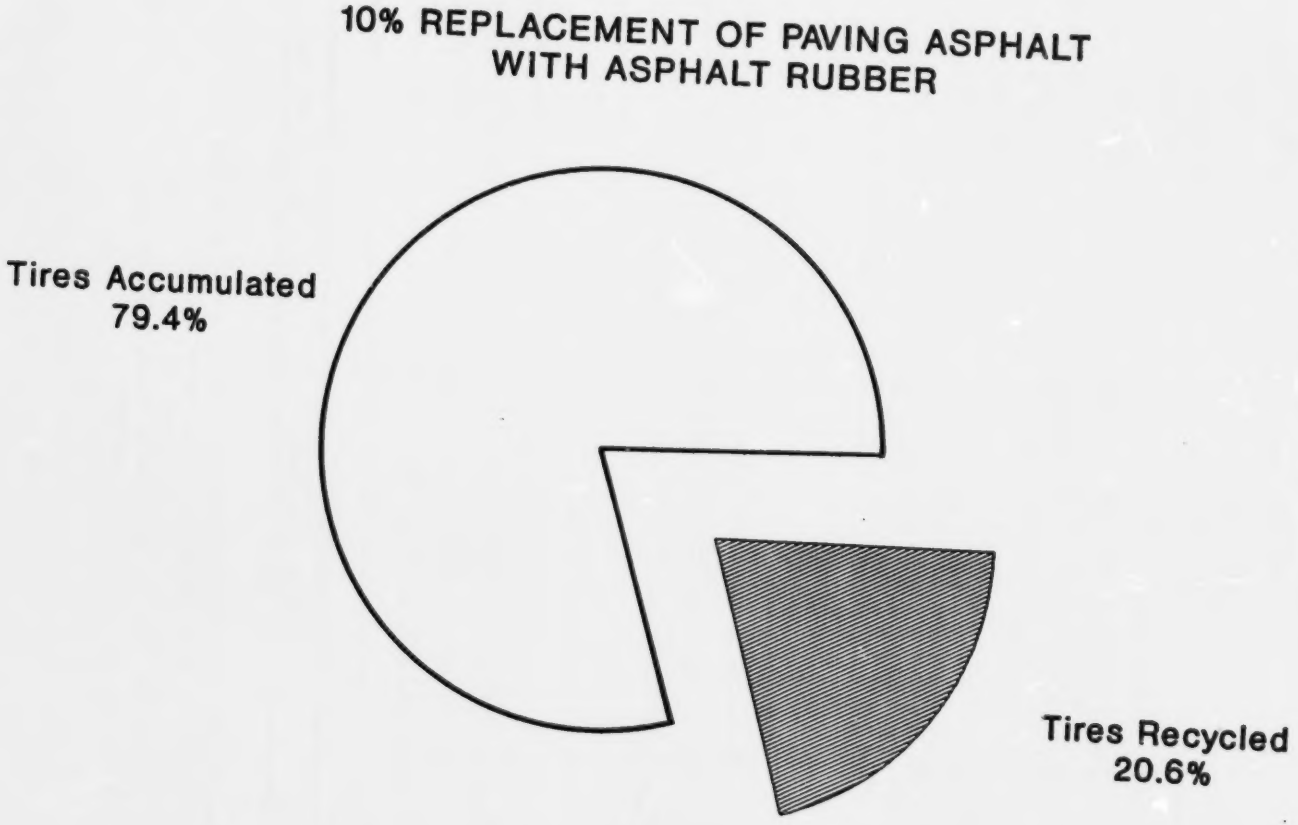


Figure 3. Effect of SDHPT Usage of Asphalt Rubber on Annual Accumulation of Scrap Tires in Texas.

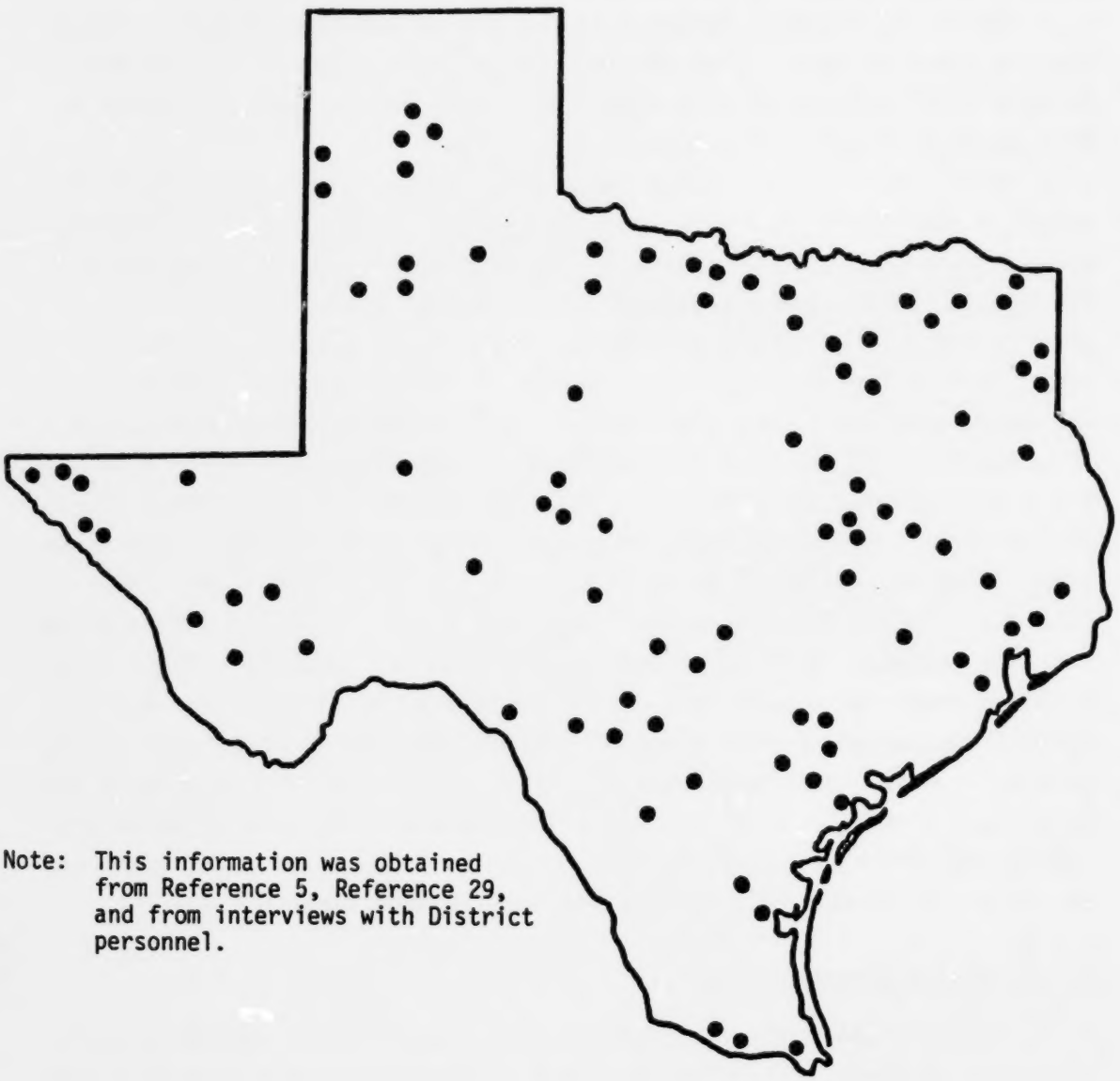
rubber was used in the modified binder and that 12 pounds of rubber per tire (60 percent of 20 pounds) were used, this quantity of asphalt rubber would account for approximately 430,000 scrap tires. However, it should be pointed out that presently more than 85 percent of these tires are coming from out of state.

Crafco, of Chandler, Arizona, is the largest supplier of asphalt-rubber crack sealants to Texas. They get most of their tire rubber from Baker Rubber in South Bend, Indiana but also receive some from Spartan Rubber in Barberton, Ohio and Atlos Rubber in Los Angeles, California.

According to asphalt-rubber suppliers and tire-rubber suppliers to the asphalt-rubber industry, a continuous supply of 1 to 3 million tires annually, a significant amount of real estate, and about 1 million dollars in capital will all be required to open and maintain operations of a profitable facility for grinding tire rubber for use in asphalt. There is one producer of ground tire rubber at this time in Texas with plants in Ft. Worth and Mexia. The plant in Ft. Worth is called "Texas Tire Disposal," and in Mexia, "Granular Products". It is reported that next year, this producer will have the capability of handling 4 to 6 million tires per year. This year, 1990, Cox Paving, placed about 10,000 tons of asphalt rubber in Texas, and used 600,000 pounds of rubber from Texas tires. However, it should be noted that the availability of crumb rubber in Texas is a rapidly changing issue. There are several reports of others going into this business. Mono-Chem Incorporated of Atlanta, Texas claim they will be producing crumb rubber next year. They hope to get into the market of asphalt-rubber crack sealants as well as producing crumb rubber for asphalt-rubber paving materials. Mono-Chem Incorporated is estimating that they will be able to use three to four million tires per year. Mono-Chem will be grinding whole-tire rubber. The fiber portion of the tire will be sold to a buyer in Tennessee and the steel will be sold to a foundry (not known at this time).

USE OF ASPHALT RUBBER IN TEXAS

Figure 4 shows the location of most asphalt-rubber paving projects throughout the state. This illustrates that all districts have experimented with asphalt rubber as a paving material. As stated previously, the Texas SDHPT currently uses 12,000 to 14,000 tons of asphalt rubber in paving operations annually. Another 1200 tons is used as asphalt-rubber crack sealants. The



Note: This information was obtained from Reference 5, Reference 29, and from interviews with District personnel.

Figure 4. Asphalt-Rubber Paving Projects in Texas (includes both asphalt-rubber seal coats and asphalt-rubber interlayers).

amount of asphalt rubber used as a paving material is compared to other modified binders in Figure 5.

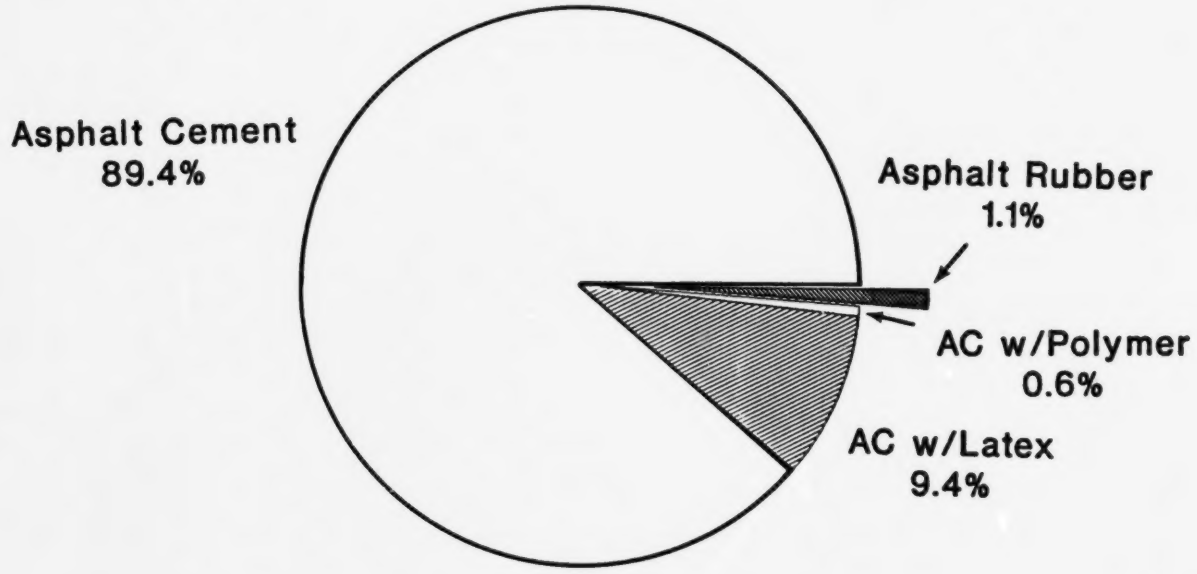


Figure 5. Current Unmodified Asphalt Binder Usage Compared to Modified Binder Usage.

ASPHALT-RUBBER CHIP SEALS (SAMs)

EXPERIENCES IN OTHER STATES

An asphalt-rubber chip seal is sometimes referred to as a stress-absorbing membrane or SAM. A comprehensive evaluation (3) was performed by the Texas Transportation Institute in 1985 documenting the performance of asphalt rubber all over the United States. The purpose of this research was to evaluate 210 installations in the 48 contiguous states where ground tire rubber had been used in pavement construction. Asphalt-rubber chip seals were included in this evaluation. Sixteen state highway departments pooled research funds to finance this task and the research was administered by the Federal Highway Administration. To provide an objective means of comparison, a system for evaluating all projects on an equal basis was devised. This system compared asphalt-rubber test sections with control sections. The performance of the two were judged based on relative performance. An Improvement Rating Scale (IRS) from -3 to +3 was developed. Positive numbers indicated experimental asphalt-rubber sections provided improvement over control sections. Negative numbers indicated the opposite trend. Relative IRS values then provided an indication of how improved or detrimental the asphalt-rubber treatment was compared to a corresponding control. This study concluded that the asphalt-rubber chip seals displayed a negative performance when compared to the control sections. This negative performance did not appear related to fundamental material characteristics, but rather to construction practices. Flushing distress was the primary cause for negative performance of asphalt-rubber chip seals and this occurred due to inappropriate application quantities of binder and aggregates.

Results from additional research performed in other states is shown in Table 2. Arizona is the pioneer state in the use of asphalt rubber. Asphalt-rubber materials have been placed on over 700 miles of roadway on the State system (4). This is approximately ten percent of the Arizona Department of Transportation (ADOT) highway network. Although regularly used on the Interstate system, the principle use has occurred on State and U.S. routes. The major application has been in mitigating reflective cracking with over 90 percent of the applications consisting of SAMs and SAMIs. A SAMI is a Stress-Absorbing Membrane Interlayer. (See Definitions Section at front of report.) Arizona

Table 2. Results of Research in Other States on Asphalt-Rubber Chip Seals.

Research Study	Research Performed	Cost Information	Performance	Conclusions
California L. de Laudenfels, "Effectiveness of Rubberized Asphalt in Stopping Reflection Cracking of Asphalt Concrete (Interim Report)," California DOT, 1985.	Eleven completed asphalt-rubber chip seal projects constructed since 1979 are reported on.	Asphalt-Rubber chip seal costs 2 to 3 times more than conventional chip seal.	In general, the asphalt-rubber chip seals are reported as performing well. Two of the projects are reported as performing well after ten years of service. Some of the projects experienced performance problems; however, the problems were not attributed to the asphalt rubber itself but to such things as an inexperienced contractor, environmental extremes, and construction deficiencies.	California is now using asphalt-rubber chip seals where cheaper chip seals and slurries are not used because of temperature and traffic problems; also, where the amount of cracking is excessive and yet major rehabilitation is not warranted. Evidence has been seen that double layers of asphalt-rubber chip seals can cover excessive alligator cracking and provide long life with no evidence of cracks coming through.
Connecticut Stephens, "Recycled Rubber in Roads-Final Report," University of Connecticut, 1981.	Four asphalt-rubber chip seals were constructed in 1978 and 1979. Performance was compared with control sections which were sand-emulsion seals.	Asphalt-rubber chip seal cost 2.5 to 3 times more than the sand-emulsion seal.	After 2 and 3 years, all of the four test roads are performing better than the controls. In general, there was no trace of the multitude of cracks which were present in the underlying surface. "The overall result has been the best seals in the area. The sand-emulsion seal to either side displayed substantial cracking when three months old." Problems which occurred were attributed to an incorrect lap in the spray bar. In some areas where the binder was of insufficient depth, stone loss has occurred.	Asphalt-rubber binder provides a long-lived flexible binder which resists the formation of cracks better than the emulsion-sand seal. The cost of the asphalt-rubber chip seal is double that of a sand emulsion seal, but the life is several times greater.
Colorado Laforce, "Crumb Rubber Chip Seal," Colorado DOT, 1986.	Four different test sections were constructed in 1978 on State Highway 94: 1) Asphalt-rubber chip seal with 25% rubber content, 100% vulcanized 2) Asphalt-rubber chip seal using 20% rubber content, 40% vulcanized, 60% devulcanized 3) AC-10 chip seal 4) RC-800 + polymer chip seal.	Asphalt-rubber chip seal cost 3 times more than RC-800 + polymer chip seal.	All of the chip seals have performed well. Chip retention has been good contributing to excellent skid resistance on the entire project. All of the chip seals have controlled the raveling of the old pavement. None of the chip seals controlled the linear cracking.	The RC-800 with polymer performed as well as either of the asphalt-rubber chip seals. Even with the limited amount of RC-800 + polymer used on this project, its cost was one-third that of the asphalt-rubber, making it a more favorable product from an economic standpoint.
Arizona Scofield, "The History, Development, and Performance of Asphalt Rubber at Arizona DOT," Arizona Transportation Research Center, 1989.	The performance of asphalt-rubber is evaluated by utilizing historical data from Arizona DOT's pavement management system database and by reviewing experimental projects. Pavement condition distress surveys were performed on several of these projects to determine the terminal condition of the pavement.	Not Available	Pavement survival curves were developed utilizing the PMS data through 1988. SAM's on the interstate perform significantly different than on state or U.S. routes.	The average life of an asphalt-rubber chip seal is approximately five years on the interstate, eight years for the U.S. routes, and ten years for the state routes.

reports that the average life of an asphalt-rubber chip seal is approximately five years on the Interstate, eight years on U.S. routes, and ten years on the State routes. The coefficient of variation in mean service life ranges between 30 and 40 percent for all three highway classifications.

OTHER RESEARCH IN TEXAS

Texas Transportation Institute

A research study (5) was conducted by Texas Transportation Institute in 1982 for the Texas SDHPT on asphalt-rubber membranes. An evaluation of performance was made for forty-five separate projects in thirteen highway districts. Approximately 850 lane miles of highways were represented by materials constructed as asphalt-rubber chip seals or SAMs. All projects reviewed were constructed between 1976 and 1981. Data on 148 conventional chip seal projects throughout Texas were reviewed and a comparison of performance was made. Some of the more significant conclusions are listed below.

1. Flushing distress occurs more often with asphalt-rubber chip seals than conventional seals at a ratio of 99 percent of all asphalt-rubber projects and 74 percent of conventional projects.
2. Shrinkage cracking appears in both asphalt-rubber and conventional seals at approximately the same level, occurring in about 50 percent of all projects.
3. With all other environmental factors equal, alligator cracking appears in conventional seals at approximately twice the frequency as in asphalt-rubber chip seals.
4. Shelling of the cover stone appears in approximately 44 percent of the conventional seals as compared to 17 percent of the asphalt-rubber seals.
5. The improved alligator cracking and raveling performance of asphalt-rubber chip seals and poorer flushing performance should not be surprising. With relatively high application rates for the asphalt-rubber binder, one might expect increased incidence of flushing distress. The increased embedment depth leads to a lower potential for raveling distress.

6. The present performance of asphalt rubber suggests that improved design methods for these new systems may alleviate the problems described here.

District 24 - El Paso

District 24 has applied a total of 606 lane miles of asphalt-rubber SAMIs and 1751 lane miles of asphalt-rubber chip seals or SAMs (6). Documentation of some specific case histories follow.

Reports on asphalt-rubber chip seals ranged in age from one to eight years. Average daily traffic volumes varied from a low of 630 to a high of 29,000 ADT. Major cracks in the old pavements were sealed prior to the application of the asphalt-rubber chip seal. Cracks reflected through the SAMs by the second winter but were only "hairline" cracks. These cracks tended to heal during the following summer. District Engineer Joe Battle states (6), "This is the best life-cycle cost we have found for the rehabilitation of cracked, weathered asphalt surfaces needing only a chip seal".

A recent project constructed by District 24 is currently under evaluation. This project was placed on IH-10 on a section of roadway about 20 years old. The highway traverses an arid region having an annual rainfall of approximately 12 inches at an average elevation of 4000 feet above sea level. It was originally constructed using eight inches of crushed limestone base, topped with three inches of asphalt-stabilized base and surfaced with eight inches of continuously-reinforced concrete pavement (CRCP).

In 1987, the hot-mixed asphalt concrete (HMAC) shoulders were rehabilitated by cold milling an 18-inch width next to the concrete pavement, placing new HMAC in that area, routing the joint and filling with hot-poured asphalt rubber. The shoulders were then chip sealed. However, during this rehabilitation project, water was observed emanating from the joints and later evidence of "pumping" was seen in the transverse cracks in the concrete pavement. These cracks soon began to widen. Department personnel felt that this could lead to a serious problem in the near future resulting in more rapid deterioration of the CRCP and that some type of preventive maintenance was urgently needed.

The only economically feasible method to waterproof the concrete pavement as determined by District 24, was to place an asphalt-rubber chip seal on the

pavement. The following summer, a second asphalt-rubber seal was placed, in effect creating a two-course surface treatment. At this time the surface looks excellent and no problems are anticipated. There are only about 500 linear feet out of about 100 miles that show any evidence of subsurface moisture where it was evident prior to this treatment.

The typical practice of District 24 is to use asphalt rubber on their three main highways: I-10, U.S. 90, and U.S. 62/180 from El Paso east to New Mexico. Because of the costs associated with asphalt rubber, it is considered cost-effective only when used on the higher traffic-volume roadways, but "Yes, it is cost-effective" states Mr. H.L. Surratt, District Operations Engineer. It is reported as lasting twice as long as a conventional seal. In El Paso, a conventional chip seal is reported as lasting seven years and an asphalt-rubber chip seal is reported as lasting 14 years.

Conclusions about asphalt rubber after a number of years of experience in District 24 are given below (6).

1. An excellent material for use in a dry, hot area. ["I have reservations for use in other climates." H. L. Surratt]
2. Should use only precoated aggregate. Best results will be obtained using 3/8-inch maximum size.
3. Restrict "asphalt (construction) season" to hottest months of the year - we restrict to June, July and August.
4. Permit seal application on very high-traffic volume roads.
5. Most things applicable to conventional seal coats apply to this material - this is a very 'forgiving' material.
6. General appearance of seal is best after about three years.
7. "This is the only significant, economically feasible, advancement I have seen in asphalt technology during my 40 year plus career with the Texas Highway Department." Quote by Mr. H. L. Surratt, District 24 Operations Engineer.

TEXAS HIGHWAY DISTRICT SURVEY

As a part of this study, a telephone survey of all the districts in Texas was conducted. Texas is divided into 24 highway districts, and personnel in each

district were queried regarding their experiences with asphalt rubber.

While there are a significant number of asphalt-rubber projects in Texas as shown in Figure 4, many of these were built on an experimental basis and the use of asphalt rubber in most districts is not standard practice. These districts are shaded in Figure 6. The primary reason cited by most districts for not using asphalt rubber is that it is too expensive. Some of these districts, which have used asphalt rubber in the past but have no future plans, report that there were some performance benefits associated with the material, but the benefits do not offset the additional cost. District 21, tried an asphalt-rubber chip seal five years ago but believes a conventional AC chip seal is just as good.

During the earlier years of asphalt-rubber technology, many of the performance problems which emerged were due to poor design and construction techniques. Now asphalt-rubber technology is more advanced and improved. Those districts which are beginning to give asphalt-rubber chip seals another try and those which use asphalt-rubber chip seals on a somewhat regular basis are shaded in Figure 7. District 17, uses asphalt rubber on a regular basis. Arthur Geick, Managing Resident Engineer in Brenham, states, "When the pavement is badly cracked but appears structurally sound, asphalt rubber is the answer". Mr. Geick says that he uses asphalt rubber as often as his budget will allow.

COST-EFFECTIVENESS

To determine the cost-effectiveness of an asphalt-rubber chip seal, the life of that seal must be known. There are many variables that affect the life of any pavement surface: environment, traffic, quality of construction and materials, condition of pavement prior to surfacing, design, and substrate. Even with construction techniques which are backed by many years of experience, such as conventional chip seals, it is difficult to estimate the serviceable life of a chip seal for a given roadway class and condition. For asphalt-rubber chip seals, this task is even more difficult. Arizona (4) reports that the life of an asphalt-rubber chip seal is five years on the Interstate, eight years on U.S. routes and ten years on State routes. District personnel in El Paso report that, on U.S. highways, the life of an asphalt-rubber chip seal is 14 years while a conventional chip seal lasts seven years. It must be kept in mind that the

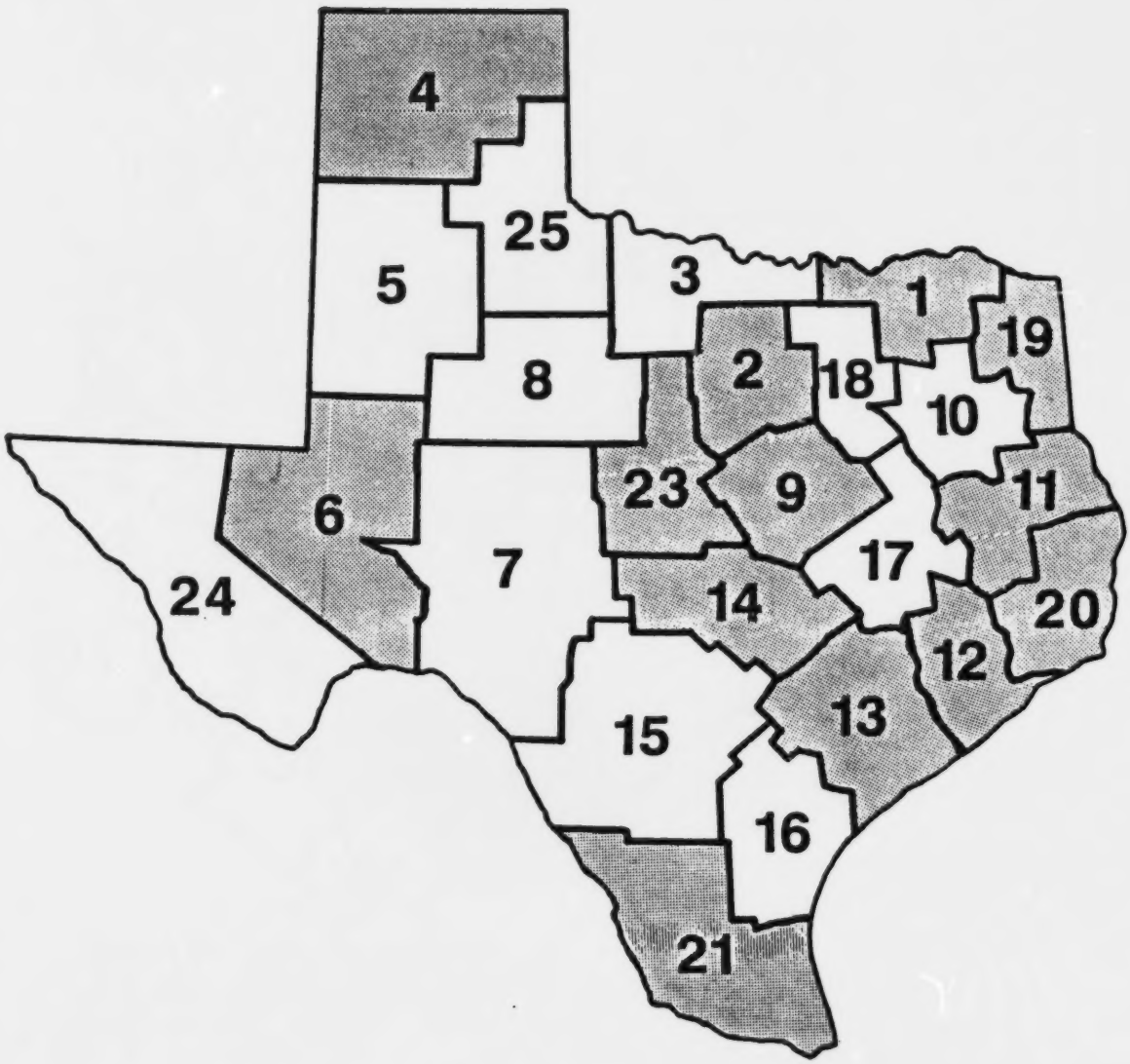


Figure 6. Districts With No Interest in Using Asphalt-Rubber Chip Seals in the Near Future.

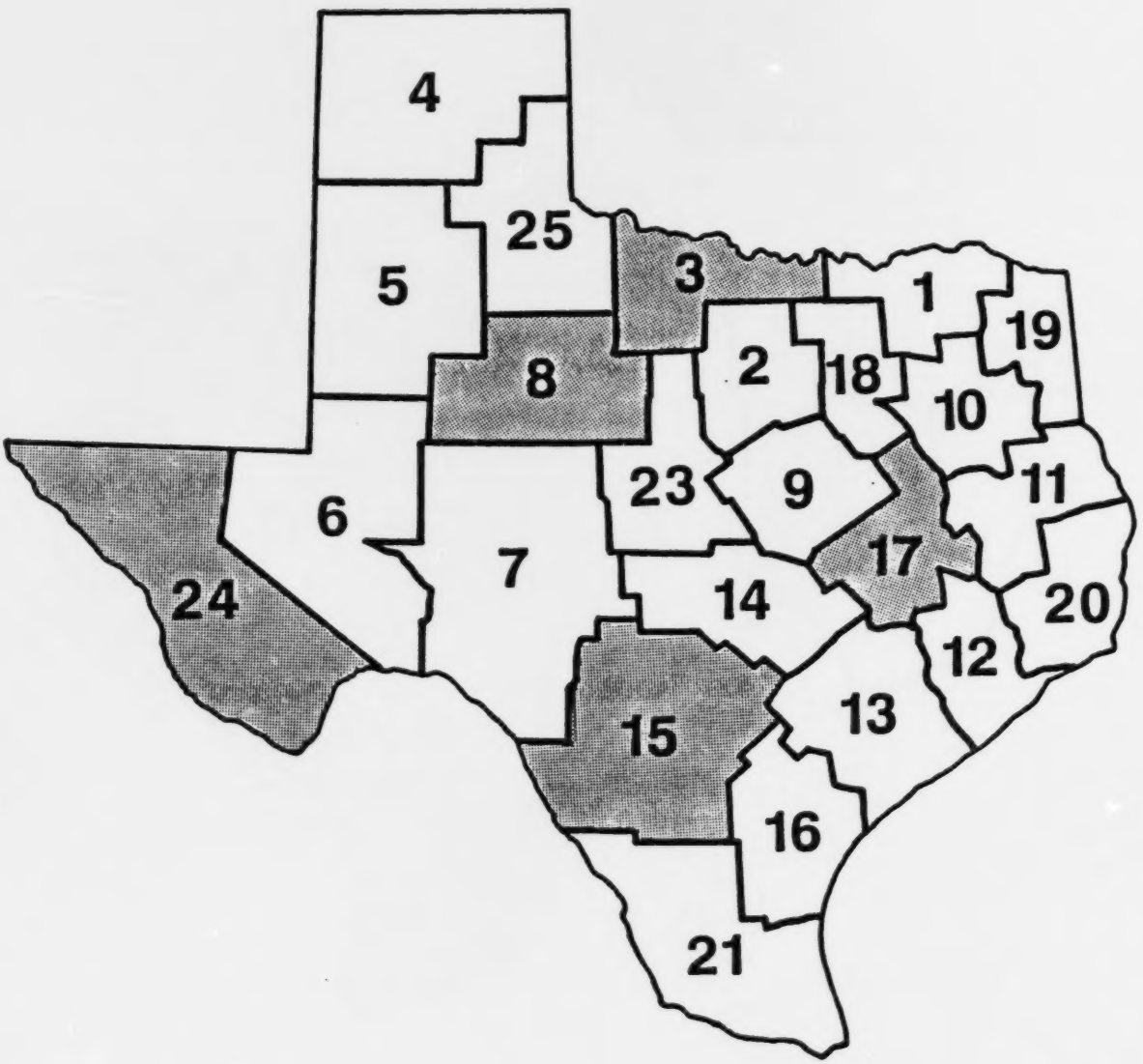


Figure 7. Districts Currently Using Asphalt-Rubber Chip Seals.

climate in both El Paso and Arizona is very arid. In an area of low rainfall, a badly cracked pavement may remain structurally sound longer than in a wet region. If a pavement is structurally sound prior to placement of an asphalt-rubber chip seal or any type of chip seal, that seal is likely to have a relatively long life.

Because of the many factors influencing the life of any pavement surface, it is very difficult to assess the cost-effectiveness of asphalt rubber. While reports of experience with asphalt rubber in some locations are quite good (4, 6), research results from across the United States (3, 5) do not indicate there are significant improvements in performance with asphalt-rubber seals over that of conventional seals. However, it must also be kept in mind that much of the research involving asphalt rubber was done at a time when the technology was still in an experimental stage. Many reports of negative performance were related to improper construction and design practices rather than to the material itself. With the present state of the art on asphalt rubber, it is not possible to accurately estimate the life of asphalt-rubber seals under specific climates, traffic conditions and underlying pavement conditions. For the purposes of this study, an annualized cost evaluation was performed for a range of service lives of an asphalt-rubber chip seal, conventional chip seal, and thin overlay. To determine the costs of conventional chip seals, and asphalt-rubber chip seals, actual construction bids from 1989 were reviewed (see Appendix B). All compared bids were for jobs of over 2,000,000 square yards which were constructed with Grade 4 aggregate. These costs along with costs for chip seals using other binders are shown in Figure 8. The following are unit costs for the different pavement surfaces used to calculate annualized costs for different pavement lives:

Conventional AC Chip Seal,	$.47/sq. yd.
Asphalt-Rubber Chip Seal,	$1.14/sq. yd.
Thin Overlay, one-inch	$1.60/sq. yd.

The cost of the overlay is based on an in-place cost of 30 dollars per ton of HMAC. The formula for equivalent uniform annual cost used in this analysis is:

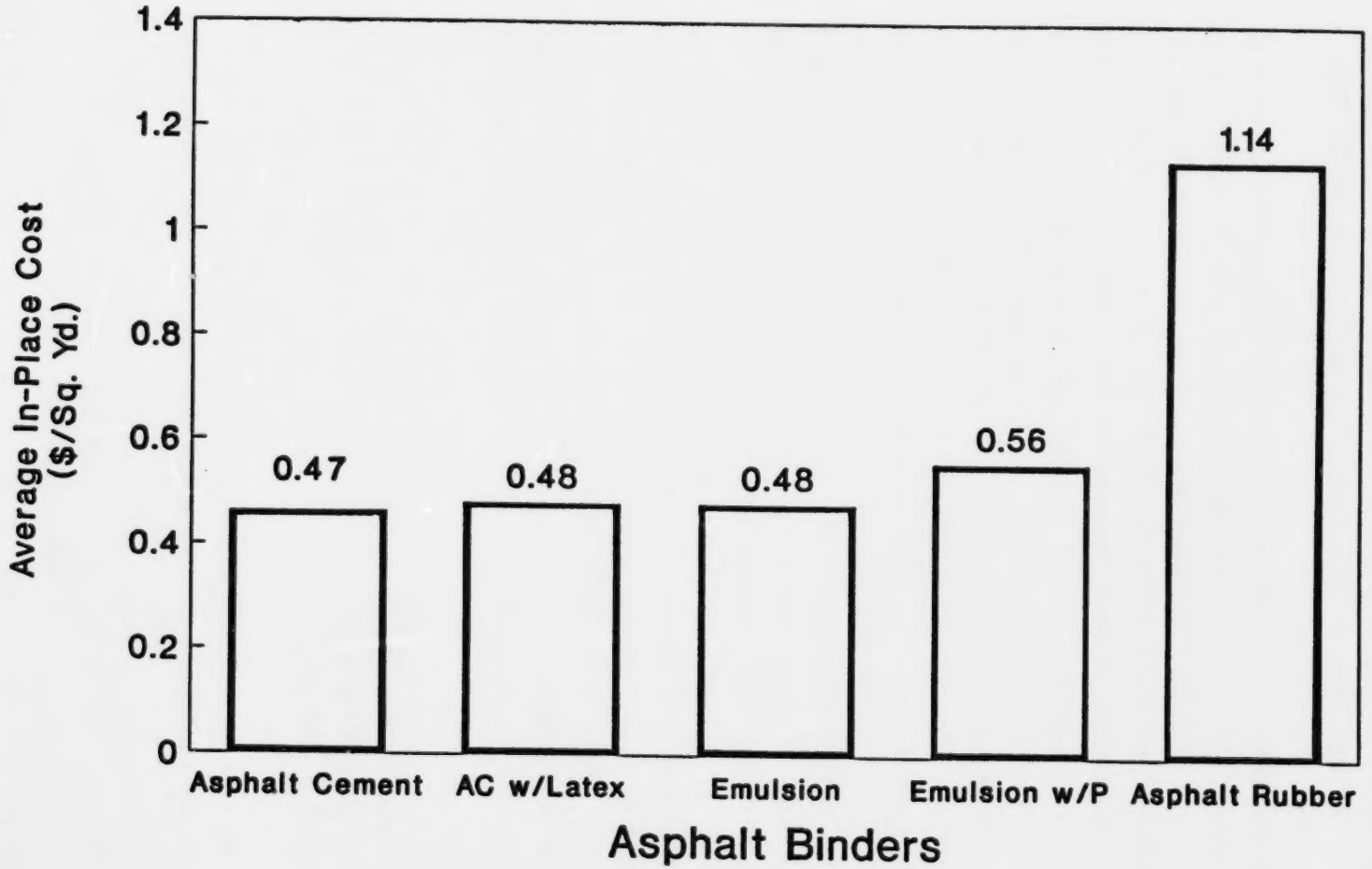


Figure 8. Typical In-Place Costs for Chip Seals Constructed with Different Binders in 1989.

$$A = \frac{P\,[i * (1 + i)^n]}{[(1 + i)^n - 1]}$$

where,

A = equivalent uniform annual cost
P = initial construction cost
i = interest rate
n = pavement life in years

It must be kept in mind that the annualized cost is based on initial construction cost only with an effective interest rate of four percent (interest rate with inflation accounted for). It does not include any user costs or expected maintenance costs.

When comparing a conventional AC chip seal to an asphalt-rubber chip seal, based on this analysis, an asphalt-rubber chip seal would have to last three times longer than a conventional seal to have the same annual cost. While this may be possible, there is little information to document these service life extensions in the field. As stated earlier, El Paso reports that the asphalt-rubber chip seal lasts twice as long as the conventional seal. Arizona reports a maximum life of ten years on a State route. It is commonly reported that a conventional chip seal will last seven years in Texas. The asphalt-rubber seal would have to last 21 years to have an equivalent cost. This seems unlikely. However, seven years is an average chip seal life for all types of roads. Asphalt rubber is usually only placed on high volume roads where a conventional chip seal might have a much shorter life of three to four years.

Originally, it was intended to compare asphalt-rubber chip seals to polymer-modified chip seals. Most of the districts in Texas at the present time use a polymer-modified AC or polymer-modified emulsion for standard chip seal construction. The addition of a polymer into the binder does not significantly increase the bid price of the chip seal for relatively large jobs (see Appendix B). In fact, many bids show an equivalent cost per square yard of chip seal. While there is no doubt that the addition of latex into asphalt increases the cost of the binder, this is not evident in the overall cost of the chip seal

examined in this study as shown in Figure 8 and Appendix B. There are several factors that enter into the cost of the chip seal: size of job, aggregate, traffic control, mobilization, and location of job. For the jobs examined herein, the latex-modified chip seals were not really any more expensive than the conventional AC chip seal. Another possible explanation for this is that when using a latex-modified asphalt, less binder may be required than for a conventional AC chip seal. While those districts that use polymer-modified binders report that there are benefits associated with the material, none are able to identify whether or not there is actually an increase in the service life. Therefore, the polymer-modified chip seals were not included in the cost analysis since they appear to be similar in cost to a conventional chip seal (on a square yard basis) as shown in Figure 8. Furthermore, no information is available regarding the life of a polymer-modified chip seal.

It should be pointed out that an asphalt-rubber chip seal contains more binder than a conventional chip seal. The conventional chip seal used in this analysis contains 0.35 gallons of AC per square yard, while the asphalt-rubber chip seal contains 0.55 gallons per square yard. Because of this difference, comparisons to conventional chip seals are not completely valid. Engineers in the Department who have experience with asphalt rubber often report they do not use this material in a location where a conventional chip seal is a viable option. An asphalt-rubber chip seal is typically used as a rehabilitative measure rather than a preventive measure when a pavement is badly cracked. Therefore, a bigger burden is often placed on an asphalt-rubber chip seal than on a conventional chip seal. Jacobson and Schnormeier (7) of the Asphalt Rubber Producer's Group report that asphalt rubber applications have been most successful when the pavement lost 80 to 90 percent of its quality, and funds were not available to reconstruct.

Perhaps a more valid performance comparison for an asphalt-rubber chip seal would be with a thin overlay. If an asphalt-rubber chip seal lasted nine years, a thin overlay (one-inch thick) would need to last 14 years to have an equivalent annual cost.

Jacobson and Schnormeier (7) have reported on the cost-effectiveness of asphalt rubber SAMs. "Cost comparisons are usually based on the direct cost of asphalt rubber versus conventional asphalt. This is O.K., if one is concerned only with initial cost. It becomes very important that all costs be included

today and tomorrow. Initial asphalt-rubber costs are twice as much as a conventional asphalt. This is a disadvantage because the money made available must be used to cover as much as the public can and will accept." Jacob and Schnormeier (7), however, conclude that asphalt rubber is cost-effective because less maintenance is required of asphalt-rubber chip seals than of conventional asphalt chip seals.

SUMMARY

Much of the early research shows that asphalt-rubber chip seals typically exhibit more distress than the conventional asphalt chip seals; however, this distress is attributed to construction practices rather than to the asphalt-rubber material itself. The primary type of distress in asphalt-rubber chip seals is flushing which is due to inappropriate quantities of binder and aggregate. It should be noted, however, that flushing on an asphalt-rubber chip seal is not as critical as it is on a conventional asphalt chip seal. Experienced Department personnel report that while an asphalt-rubber chip seal can be flushed on the surface, it will still have adequate skid resistance to remain serviceable for a number of years which is not true for conventional asphalt chip seals. This may be due to the rubber particle providing increased skid resistance and/or to the fact that the asphalt-rubber binder is much stiffer than an asphalt cement.

Only five of the 24 districts in Texas currently construct asphalt-rubber chip seals on a somewhat regular basis. More than half of the districts have no plans for building asphalt-rubber chip seals in the foreseeable future. The primary reason cited by most districts for not using asphalt rubber is that it is too expensive. However, personnel in District 24, El Paso, and District 17, Bryan, which use asphalt-rubber chip seals regularly report that it is a cost-effective treatment when built properly and used in appropriate situations.

Because of the many factors influencing the life of any pavement surface, it is very difficult to assess the cost-effectiveness of asphalt-rubber chip seals. While reports of experience with asphalt rubber in some locations are quite good, research results from across the United States do not indicate there are significant improvements in performance with asphalt-rubber chip seals over that of conventional chip seals. However, it must also be kept in mind that much of the research involving asphalt rubber was done at a time when the technology

was still in an experimental stage. Because an asphalt-rubber chip seal costs two to three times more than a conventional chip seal, it is difficult to justify its cost-effectiveness. However, asphalt rubber is not typically used in applications where a conventional chip seal is an option. It is often used successfully as a rehabilitative measure rather a preventive measure. Or it is used on pavements with a high volume of traffic where a conventional chip seal would not be used. Therefore, a more valid comparison for asphalt-rubber chip seals might be with a thin overlay or multiple chip seal.

ASPHALT-RUBBER INTERLAYERS (SAMIs)

EXPERIENCE IN OTHER STATES

Asphalt-rubber interlayers are sometimes referred to as stress absorbing-membrane interlayers (SAMI). This rehabilitative measure involves placing an asphalt-rubber chip seal over an existing pavement followed by an overlay of hot-mixed asphalt concrete (HMAC). In a SAMI, theoretically, the asphalt rubber will absorb the stresses being produced in the underlying pavement thereby reducing the rate at which the cracks in the underlying pavement reflect through to the new surface. A study conducted by the Texas Transportation Institute (3), as mentioned in the previous chapter, evaluated the performance of asphalt-rubber interlayers placed in the 48 contiguous states of the U.S. In this study, it was found that when asphalt-rubber interlayers are used for appropriate distress and properly constructed, improved overlay performance can be achieved. Some performance problems were observed with the asphalt-rubber interlayers but were attributed to construction practices.

Results from additional research performed in other states is shown in Table 3. Arizona (4) reports performance data for SAMIs in Table 4. Surprisingly, SAMIs appear to last longer on interstate than on state and U.S. routes. This is probably due to the fact that interstate pavements were in better condition at the time of the SAMI placement and received approximately twice the overlay thickness. The coefficient of variation for SAMI life for all classifications was between 41 and 45 percent, a significant performance variability.

Morris et. al. (8) used a finite-element procedure as an aid in explaining why a SAMI can be used effectively to eliminate reflective cracks. It was found that a SAMI can significantly reduce stresses at the crack tip due to thermal and traffic loads and provide longer service life of the asphalt concrete surface layer.

SAMI RESEARCH IN TEXAS

Texas Transportation Institute

The Texas SDHPT is sponsoring an ongoing research study with the Texas Transportation Institute (9) to evaluate the performance of asphalt-rubber

Table 3. Research in Other States on Asphalt-Rubber Interlayers.

Research Study	Research Performed	Cost Information	Performance	Conclusions
Connecticut Stephens, "Recycled Rubber in Roads-Final Report," University of Connecticut, 1981.	Two test roads were constructed with SAMIs over old bituminous concrete pavements. Three types of overlays were placed over the interlayer: (1) conventional hot-mix, (2) hot mix with 1% reclaimed rubber, (3) hot mix with 2% reclaimed rubber. The overlay was 1 1/2 to 2 inches thick.	The SAMI alone was 20 - 30% of the total cost of the SAMI and overlay combined.	There is no appreciable evidence that the asphalt-rubber overlay is performing better than conventional hot-mix. Both test roads show approximately 50% less cracking in the portions over the SAMI after 2 years.	1. Reflection cracking was less where an interlayer was present. 2. The crack reduction brought about by a stress relieving interlayer was not additive to that from an asphalt-rubber overlay. That is, the performance of an asphalt-rubber overlay combined with a stress-relieving interlayer was about the same as either alone.
Washington Allison, "Rubber Asphalt Binder-Stress Absorbing Membrane Interlayer," Washington DOT, 1989.	A SAMI was placed in 1978 on a 10-year old bituminous pavement with alligator cracking in the wheel paths. The new overlay was 1 1/2 to 2 inches thick. The control section had no SAMI.	Not Available	To date, 10 years later, reflective cracking has appeared in neither the SAMI test section nor the adjacent control.	After 10 years with no evidence of distress in either the control or test areas, it is believed that the overlay depth was sufficient to mask the benefits of the SAMI.
	A SAMI was placed in 1978 over a 20-year old bituminous pavement with continuous alligator cracking. The new overlay was 1 1/2 to 2 inches thick. The control section had no SAMI.	Not Available	Ten years later, no reflective alligator cracking has appeared in the SAMI test section or the control.	No conclusion can be made at this time regarding the effectiveness of the SAMI for reflective crack prevention or reduction. It is believed that the depth of the overlay was sufficient to mask the effects of the SAMI.
Arizona Scofield, "The History, Development, and Performance of Asphalt Rubber at Arizona DOT," Arizona Transportation Research Center, 1989.	The performance of asphalt rubber was evaluated by utilizing historical data from Arizona DOT's pavement management system database and by reviewing experimental distress surveys performed on several of these projects to determine the terminal condition of the pavement.	Not Available	SAMI's appear to last longer on interstates than on state or U.S. routes. This is probably due to the fact that interstate pavements were in better condition at the time of SAMI placement and received approximately twice the overlay thickness.	The average life of a SAMI is approximately nine years on interstate and state routes while it is only three years on the U.S. routes. The coefficient of variation for SAMI life for all classification was between 41% and 45%, a significant performance variability.

Table 4. Performance Data for SAMIs in Arizona. (4)

Route	Mean SAMI Life (Years)				Mean Overlay Thickness @ SAMI (inches)	Pavement Age @ SAMI (years)		Mean 18K ESALS* Since SAMI Application
	σ	C.V.	$\bar{X}$	R		$\bar{X}$	R	
Interstate	3.9	44	9	5-15	4.0	14	8-29	2676
State Route	3.9	41	9.5	3-13	2.0	19	9-32	241
U.S. Route	3.6	45	7.8	6-12	2.5	28	10-44	227

interlayers. Three full-scale test roads were constructed in 1983 and 1984 near El Paso, Brownsville, and Buffalo, Texas. The Buffalo test road has an overlay thickness between four and six inches and is not showing any distress. The Brownsville test road was constructed with excessive interlayer binder application rates and all sections are flushing. However, the El Paso test road has yielded some useful information. Nine different types of asphalt-rubber interlayers were constructed there using different binder application rates, different rubber concentrations, and different ground tire rubber suppliers. The control section contained no interlayer. All of the asphalt-rubber sections are performing better than the control in terms of delaying reflective cracking with some sections performing significantly better.

District 24 - El Paso

District 24 currently has six asphalt-rubber interlayers under observation. These range in age from one year to 12 years. Overlay thickness is from 1 1/2 to 3 inches. The average binder application rate was 0.55 gallons per square yard. All of the interlayer aggregates were Grade 4 except for one project which used a Grade 3. Traffic exceeds 100,000 ADT on some of these pavements. El Paso (6) reports that major cracks in the old pavement were sealed with asphalt rubber prior to application of the SAMIs. Cracks reflected through SAMIs by the second winter but these were only "hairline" cracks and they tended to heal the following summer. All pavements are still in good to excellent condition. "This material provides the best life cycle cost we have found for rehabilitation of cracked, weathered asphalt surfaces needing minor leveling provided by thin HMAC overlays."

SURVEY OF TEXAS HIGHWAY DISTRICTS

Personnel in each highway district were contacted to determine their experiences with asphalt rubber applied as interlayers. Those districts which have constructed asphalt-rubber interlayers are identified in Figure 9. The opinions of Department personnel on asphalt rubber used as an interlayer are much more favorable than for those used as chip seals. While the cost of an asphalt-rubber interlayer is still at least twice that of a conventional chip seal interlayer, it is only a small portion of the total overlay system cost. Most

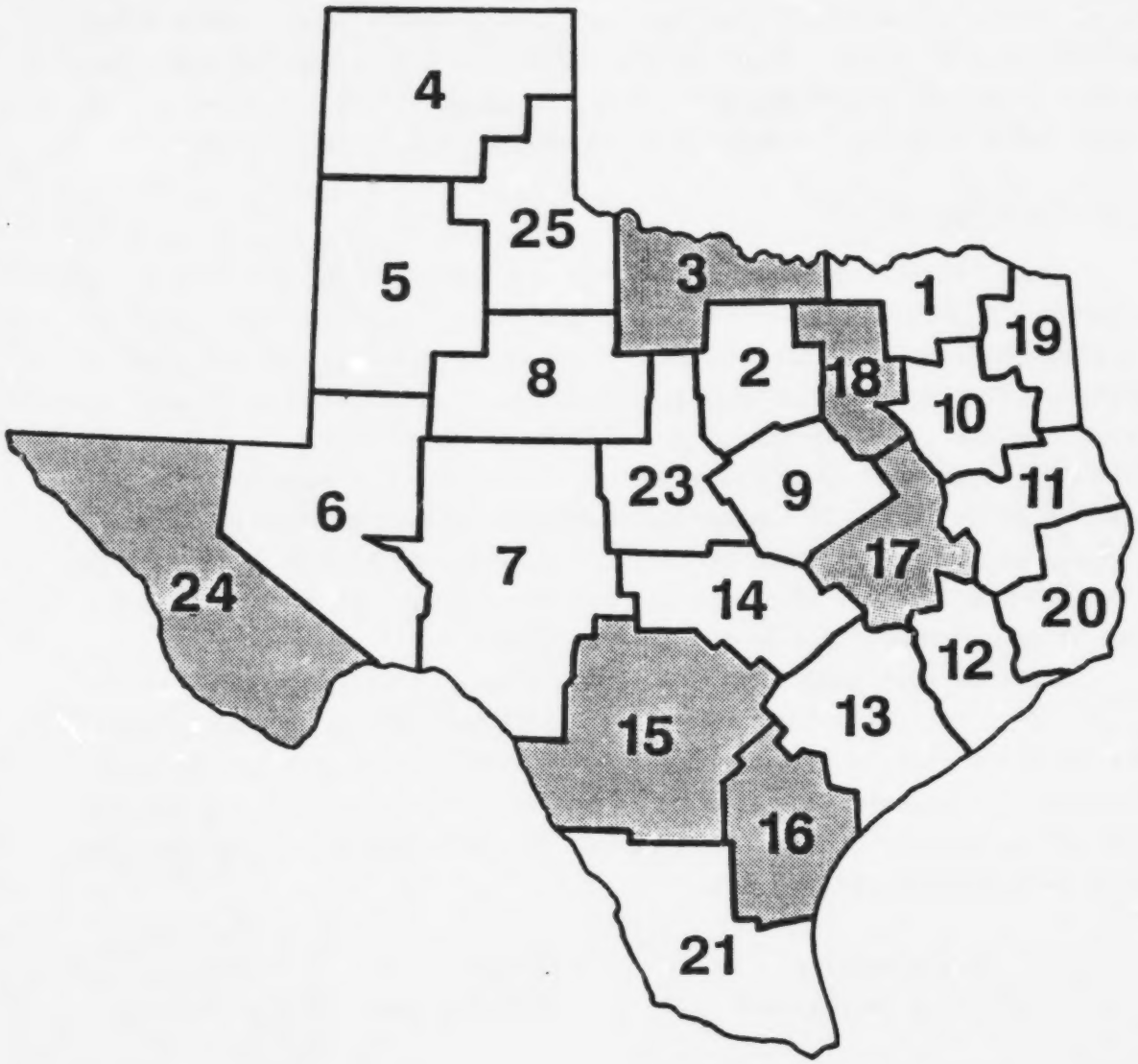


Figure 9. Districts Currently Using Asphalt-Rubber Interlayers.

of the districts which have used asphalt rubber as an interlayer report that it definitely reduces the rate of reflection cracking.

Evidence has been seen in the field of cracks in asphalt-rubber chip seals "healing" in the summer months. While this can be seen in an asphalt-rubber chip seal, this cannot be viewed in an asphalt-rubber interlayer since it is covered by an overlay. However, if this "healing" ability exists in an asphalt-rubber interlayer, then the interlayer may function as a waterproofing membrane. Once cracks do develop in the surface layer, the asphalt rubber may prevent or at least reduce any water intrusion into the underlying pavement structure.

COST-EFFECTIVENESS

Based on the literature review, research conducted by TTI, and on the experience of Department personnel, an asphalt-rubber interlayer can produce an improvement in pavement performance. While it is generally believed that an asphalt-rubber interlayer extends pavement life, it is not accurately known how long. Because the interlayer is not visible on the surface, its effects are difficult to measure. A common method of evaluation is to measure reflective cracking in the surface of the overlay. However, there may be other improvements in pavement performance which are not commonly measured by highway departments such as roughness. If there are any benefits due to "waterproofing" of the underlying structure, this is difficult to measure.

A similar cost analysis as shown in the previous chapter was performed for SAMIs. An annualized cost was determined for a 2-inch overlay and compared with the annualized cost for an asphalt-rubber SAMI with a 2-inch overlay. As in the previous cost analysis, this is based on initial construction cost only and does not include any user or maintenance costs. The following initial construction costs were used for the analysis:

2-inch overlay	$3.20/sq. yd.
2-inch overlay with SAMI	$4.25/sq. yd.

Based on this analysis, a 2-inch overlay with an asphalt-rubber SAMI would need to last approximately 50 percent longer than a 2-inch overlay alone to yield an equivalent annual cost. For example, if a 2-inch overlay lasted eight years,

a 2-inch overlay with SAMI would need to last 12 years to be equivalent in cost.

SUMMARY

Much of the research on asphalt-rubber interlayers or SAMIs is inconclusive or shows only marginal improvements in pavement performance. Because, by definition, the interlayer is covered with an asphalt-concrete overlay, it is difficult to see or measure any benefits that are derived from that interlayer. However, some research does show improvements in pavement performance in terms of reducing the rate of reflection cracking and the opinions regarding the performance of interlayers of many experienced field engineers are quite positive. There is also some evidence to suggest that the asphalt-rubber interlayer may function as a waterproofing membrane thereby protecting the underlying pavement structure from the intrusion of water.

Six of the 24 districts in Texas use asphalt-rubber interlayers on a somewhat regular basis. Overall, Department personnel opinions are more favorable for asphalt rubber used as an interlayer than as a chip seal. Most of the districts which have used asphalt rubber as an interlayer report that it definitely reduces the rate of reflection cracking.

It is not possible to determine the cost-effectiveness of asphalt-rubber interlayers with the information currently available. However, based on an annualized cost analysis comparing a 2-inch overlay with a 2-inch overlay and SAMI, the overlay and SAMI would need to last 50 percent longer than the overlay alone to yield an equivalent annual cost.

ASPHALT-RUBBER CRACK SEALANTS

GENERAL

One of the most troublesome problems the highway department faces in their effort to provide quality, long lasting pavements, is the presence of pavement cracks. In the past, maintenance forces have used many materials as sealants, in attempts to seal cracks and effectively extend pavement life. These materials include: asphalt cements, cutbacks, emulsions, and latex-modified emulsions. However, during the seventies and early eighties, asphalt rubber sealing compound containing ground tire rubber emerged as a new and comparatively effective means of crack repair. The compound is composed of approximately 80 percent asphalt and 20 percent ground tire rubber.

At the current time, over 95 percent of all asphalt-rubber crack sealant that is used in Texas is supplied from Crafco Inc. which is located in Chandler, Arizona. Crafco has done extensive research in asphalt-rubber formulation, production, and application and has helped the State of Texas in its specification guidelines for asphalt rubber crack sealant. Last year, they supplied almost 3.5 million pounds of material to Texas at an average price of 0.19¢/lb., translating to a yearly total of $495,041. This material was used to fill approximately 14 million linear feet of crack and joints. The price has varied slightly over the past several years with costs ranging from 0.12¢ to 0.15¢/lb., but may have risen lately due to a lack of competitive bidding from other suppliers. In fact, this is a problem for the Department in that it appears that Crafco has a patent on the asphalt-rubber crack sealant which they are currently marketing and there are presently no comparative asphalt-rubber sealants being marketed in Texas. The Department is working on a solution to this problem by modifying the specification to accept a slightly different product which would allow other competitors to enter the market.

SURVEY OF TEXAS HIGHWAY DEPARTMENTS

Based on a telephone survey with district personnel in Texas, Crafco asphalt-rubber sealant is the product of choice. Many of the districts have used other products in the past, and on jobs with very small cracks a polymer emulsion product has proven to be more effective; however, the asphalt rubber continues to "last longer and provide less problems" (J. R. Blackwell, District 4) than

other types of sealants.

In talking to each of the districts with crack sealing programs, it was quickly evident that they were pleased with the product. The following are typical comments: The rubber is very stable; the tires do not displace it; the rubber provides good elasticity and strength; it doesn't seem to weather or oxidize at all.

Almost all of the districts agreed on the material's properties and all independently estimated the typical life of the product to be three years.

COST-EFFECTIVENESS

To be consistent with the rest of this report it would be beneficial to include a cost-effectiveness comparison with other similar products. However, the extensive use of the asphalt rubber throughout the districts makes this type of comparison very difficult. Projects are sometimes encountered which require other special sealants; however, these projects are usually very small and a true performance comparison cannot be established.

SUMMARY

Asphalt-rubber crack sealant is used extensively throughout Texas. It is the preferred product by all the districts. No performance comparisons were available with other materials since asphalt rubber is the predominant material used.

RUBBER-MODIFIED ASPHALT CONCRETE MIXTURES

A limited number of states have used asphalt rubber as a binder in hot-mix asphalt paving mixtures. Results of a recent survey by the Asphalt-Rubber Producers Group (ARPG) indicated that, between 1975 and 1987, at least 35 projects were placed in 12 different states that utilized asphalt rubber as a binder in the mix (11). Applications identified included construction of wearing courses overlays, and recycled mixes.

In this section, experience of various state transportation agencies in the use of asphalt-rubber mixtures is reviewed. These states include Alaska, Arizona, California, Connecticut, Florida, Minnesota, Wisconsin, and Texas. This review is followed by a performance and cost evaluation of rubber-modified asphalt concrete mixtures using materials information obtained from the literature.

EXPERIENCE IN OTHER STATES WITH ASPHALT-RUBBER MIXTURES

Experimental pavement projects involving asphalt-rubber mixtures have been constructed by several state transportation agencies. A review of applications that have been attempted in states outside of Texas is presented in the following.

Alaska

The Alaska Department of Transportation and Public Facilities has been evaluating rubber-modified asphalt pavements for more than ten years. Between 1979 and 1987, 12 experimental rubber-modified pavement sections totaling 34.1 miles in length were constructed by the Department (11). In these projects, three percent of coarse rubber particles by weight of the total mix were incorporated into the hot-mix asphalt pavement sections. The paving mixtures have been successfully prepared in both batch and drum mix plants, and placed with conventional pavers and rollers.

As of the 1987 condition survey, eight of the 12 sections were rated as good to very good. Of the four remaining pavement sections, one was overlaid in 1982, two years after it was placed, while another had a seal coat applied to it five years after construction. The other two sections showed some distress, with one section exhibiting minor rutting at an intersection, and the other some

slight to moderate flushing in the wheelpaths. Although a majority of the test sections were performing well as of the 1987 condition survey, five of the eight sections were in service for only two years or less. Thus, it is still premature to draw any definite conclusions regarding the performance of asphalt-rubber mixtures from the field observations that have been made on the projects.

Arizona

The Arizona Department of Transportation has been using asphalt rubber for pavement construction since the mid-1960's. The major application has been in mitigating reflection cracking with over 90 percent of the applications being stress-absorbing membranes and stress-absorbing membrane interlayers (12). However, since 1987, the Department has been using asphalt rubber as a binder in open-graded and dense-graded paving mixtures. The open-graded asphalt mix has a total binder content of approximately 8 percent, consisting of 80 percent AC-10 asphalt and 20 percent vulcanized rubber. The dense-graded mix has a total binder content of approximately 6 percent with the same percentages of AC-10 asphalt and vulcanized rubber as the open-graded mix. These mixtures are typically utilized as overlays and are finding increasing use. The open-graded mixture is usually placed as a 3/4 to 1-inch layer while the dense graded mixture is typically placed as a 1.5 to 2-inch layer.

California

The California Department of Transportation has been experimenting with rubber-modified asphalt mixtures for pavement overlays. The experience gained from several experimental overlay projects indicate that asphalt-rubber mixtures are more abrasion resistant and have lower permeabilities than conventional asphalt concrete mixes (13). Several projects which were built in the snow region of the state have shown greater resistance to abrasion due to tire chains as compared to projects built with conventional mixtures. This has resulted in less maintenance work for asphalt-rubber pavements. The lower permeabilities measured for asphalt-rubber mixtures are also expected to reduce problems associated with water infiltration and oxidative aging.

The Department has also been experimenting with asphalt-rubber overlays of reduced thickness since 1983. Prior to this year, asphalt-rubber projects were

being evaluated against conventional asphalt projects of equivalent thickness. However, in 1983, a project was constructed that included three asphalt-rubber test sections of reduced thickness. The Department's experience indicate that the thickness requirements for asphalt-rubber mixtures are less than those for conventional asphalt mixtures. However, it is believed that further field trials are necessary to determine the appropriate reduction in overlay thickness for a given design life.

Connecticut

In October 1980, the Connecticut Department of Transportation (ConnDOT) placed an experimental 900-foot section of an asphalt-rubber overlay on State Route 79 in Madison, Connecticut (14). Finely ground rubber was premixed with an AC-20 asphalt to produce a binder that was 80 percent asphalt and 20 percent rubber. The binder was then mixed with the aggregates to produce a bituminous mixture with a binder content of 7.5 percent. The asphalt-rubber mixture was placed as a 1.5-inch overlay. A standard ConnDOT Class 2 mix was placed at the same time to serve as a control section. An 8-year performance evaluation found that the asphalt-rubber pavement was performing better than the control pavement on the basis of transverse, longitudinal, and alligator cracking. Skid resistance and roughness values were also found to be acceptable and were similar to those measured for the control section.

Florida

There are about 15 million scrap tires accumulating annually in the state of Florida. In order to address this environmental concern, the Florida legislature passed a bill on solid waste management that instructed the Florida DOT to investigate the use of ground tire rubber in asphalt concrete mixtures and to develop the necessary changes in specifications and procedures to permit its use in asphalt pavement construction. In response to this bill, the Florida DOT funded a research project to review the state of the art on applications of ground tire rubber in asphalt concrete mixtures. This project was conducted by the National Center for Asphalt Technology (NCAT).

The major recommendation from this study was that ground tire rubber be added only to surface friction course mixtures constructed with virgin materials

(15). Although the study was initially concerned with all types of surface and structural mixes used in Florida, several technical issues related to the use of scrap rubber in recycled mixtures were identified that had to be addressed before this waste product can be used in structural mixtures. It is common practice in Florida to use reclaimed asphalt pavement materials in almost all structural mixtures. The technical issues identified in using ground tire rubber in recycled mixtures include: 1) increased air pollution; 2) unknown interaction effects between rubber and recycling agents; 3) the effectiveness of a rejuvenating agent which has reacted with rubber; and 4) potential chemical compatibility problems between rejuvenating agents and ground tire rubber. Due to the lack of research in the use of ground tire rubber in these mixtures, the recommendation was made that the initial application be in surface friction courses constructed with virgin materials until the preceding issues have been resolved.

Two demonstration projects were constructed by the Department in 1989 to evaluate the short-term field performance of fine-graded and open-graded surface friction courses constructed with varying amounts and sizes of ground tire rubber to identify problems that may arise in the construction of these pavements (16). The first project consisted of three asphalt-rubber concrete sections and one conventional asphalt section. Two test sections utilized ground tire rubber passing the No. 80 sieve preblended at three and five percent by weight of the asphalt cement. Another test section was built using ground tire rubber passing the No. 40 sieve preblended at ten percent by weight of the asphalt cement. Construction of this project indicated that the minus 80 mesh ground tire rubber preblended at five percent has the greatest potential for use as an asphalt additive for fine-graded surface friction courses. A higher percentage resulted in construction problems.

The second project utilized an open-graded surface mix and consisted of four asphalt-rubber concrete sections and one conventional asphalt section. Three test sections consisted of the minus 80 mesh ground tire rubber preblended at five, ten, and 15 percent, while the other test section was built using the minus 24 mesh rubber preblended at 17 percent. Results indicate that the ten percent, minus 80 mesh blend may be the optimum for open-graded friction courses. It was observed that higher binder contents with higher amounts of ground tire rubber resulted in pavements that appeared to have too much asphalt during

construction which may lead to flushing of the mix under traffic.

Minnesota

The Minnesota Department of Transportation constructed a project in 1984 that used asphalt rubber as a binder in a dense-graded mix (17). The project included overlaid and reconstructed pavement sections. Crumb rubber was blended with 120/150 penetration grade asphalt cement at 20 percent by weight of the cement. No changes in the standard gradations were made although a separate mix design was conducted for the asphalt-rubber mix.

Field observations have shown no difference in amounts of cracking between the asphalt rubber and conventional asphalt-concrete overlays. However, for the reconstructed pavements, the section with asphalt rubber in the binder and wearing courses showed less cracking than the other test sections. In view of the fact that the asphalt rubber costs approximately 50 percent more than conventional asphalt concrete mixtures, and of the limited results thus far, the Department does not plan to build other dense-graded asphalt-rubber sections unless further evaluations reveal more significant benefits.

In 1984, the Department also constructed two test sections using the Plus-Ride system wherein a portion of the finer material in a dense-graded aggregate is removed and replaced with ground tire rubber before the asphalt is introduced. The asphalt-rubber mixture was used as a wearing surface with the hopes that skid resistance will be enhanced, reflection cracking will be mitigated, and a self de-icing pavement will be created. However, field observations by maintenance personnel to date have revealed no significant benefits from the use of the Plus-Ride mixtures to offset the over 50 percent increase in cost.

Wisconsin

In 1987, the Wisconsin Department of Transportation constructed two experimental projects that included test sections incorporating ground tire rubber in the asphalt cement for a recycled mix (18). Performance observations made thus far show disappointing results for the asphalt-rubber mixtures. Compared to a standard recycled mix, the recycled asphalt-rubber mix developed up to five times more transverse cracking during the first two years of service. However, the Department plans to evaluate another ground tire rubber project in 1990. In this

project, an asphalt-rubber overlay will be placed on a 35 year old Portland cement concrete pavement. In contrast to the 1987 project, however, the planned overlay will not be a recycled mix.

FIELD EXPERIENCE IN TEXAS

The 1989 hot-mix asphalt concrete usage within the State of Texas is approximately 8.1 millon tons, which is down slightly from the five year average of 9.4 millon tons. These high values indicate excellent opportunities for use of asphalt rubber. However, at this time only two districts in Texas have tried the product. Ten years ago, District 21 decided to experiment with the rubber-modified hot-mix, but the job was unsuccessful. District maintenance forces were used to apply the hot-mix along a one mile section on SH336 in McAllen; the asphalt rubber reportedly did not hold at all. The mix raveled severely and the district was forced to place a chip seal over the mix within three months.

The only other District to have experimented with asphalt-rubber hot-mix, is District 10 in Tyler. This job was contracted to International Surfacing Inc., located in Chandler, Arizona, in the summer of 1989. The project was located at the intersection of FM 14 and Loop 323 just outside of Tyler. Asphalt rubber was chosen for the site in hopes of curing a severe rutting problem caused by large trucks turning onto and off of the Loop. So far, district personnel are pleased with the project and are very interested in using the product again but on a more standard hot-mix job. The cost of the asphalt rubber for this size job was approximately $80/ton. Tyler believes that a larger job would help reduce this high material cost.

Besides these two projects, little other asphalt-rubber hot-mix work has been done in Texas. In telephone conversations with several of the districts, engineers expressed interest in trying the product, but at this time only one other project is scheduled. District 4 in Amarillo has planned, a ten lane mile asphalt-rubber hot-mix job for the fall of this year. Preliminary cost estimates indicate an in-place cost of $52/ton for the asphalt-rubber paving material which is substantially less than the $80/ton reported in Tyler, but not particularly attractive when compared with the $30-$35/ton most districts pay for conventional hot-mix asphalt concrete.

PERFORMANCE AND COST EVALUATION OF ASPHALT-RUBBER CONCRETE MIXTURES

Since only a few rubber-modified asphalt concrete pavements have been built in Texas, very limited data exist on the in-service performance with which to evaluate cost-effectiveness. However, asphalt-rubber mixtures have been evaluated in previous research projects at TTI, most recently by Hoyt, Lytton, and Roberts (19) in a study conducted for the Federal Aviation Administration (FAA). In this FAA study, laboratory characterizations were performed on conventional and rubber-modified asphalt concrete mixtures from which resilient modulus, fatigue, creep, and permanent deformation data were obtained. The materials data from this FAA study were used herein to evaluate the expected field performance of rubber-modified asphalt concrete pavements and to estimate their cost-effectiveness. It is recognized that because of the limited amount of information on in-service performance, no definite conclusions may be made regarding the cost-effectiveness of asphalt-rubber pavements. The performance evaluation presented herein is primarily an attempt to estimate the potential cost-effectiveness of asphalt-rubber concrete. Full-scale field studies are necessary to verify whether the results from the analysis are borne out in practice.

Materials Information Used in the Evaluation

Available data from the literature on material properties of asphalt-rubber mixtures were used herein to predict the field performance of asphalt-rubber pavements. In the performance evaluation, the asphalt-rubber mix was compared to conventional and additive-modified asphalt concrete mixtures. The material properties for the different mixtures were obtained from the FAA research project mentioned previously and from an FHWA study on asphalt additives that was also conducted at TTI (20). The materials information obtained from these studies are discussed in detail in Appendix C. In addition to presenting the materials data collected in the FAA and FHWA studies, Appendix C explains the various laboratory tests that were conducted and how the measured data relate to pavement performance. The interested reader is encouraged to go over this appendix to gain a more complete understanding of how the expected performance of conventional, rubber-modified, and additive-modified asphalt concrete pavements were predicted herein. Only a concise summary of the predictions obtained are

presented in the following paragraphs.

Performance Evaluation of Asphalt-Rubber Concrete Mixtures

The performance evaluation of asphalt-rubber concrete mixtures was conducted using a mechanistic finite element program called FLEXPASS developed by Tseng and Lytton (21). FLEXPASS, an acronym for FLEXible Pavement Analysis Structural System, is based on modifications made to the ILLI-PAVE program developed at the University of Illinois. Within the FLEXPASS program are models for predicting the progression of fatigue cracking, rutting, and serviceability loss with increasing axle load applications. The program uses as input fundamental material properties such as resilient modulus, fatigue, creep, and permanent deformation characteristics to predict pavement performance.

For the evaluation of asphalt-rubber concrete mixtures, a hypothetical pavement section consisting of a 6-inch bituminous bound surface layer, and a 10-inch granular base course overlaying a clay subgrade was assumed. A 9000 pound single wheel load at an inflation pressure of 75 psi was used to represent the standard 18-kip single axle load. A traffic rate of 150 18-kip ESAL/day was used in the simulation.

Properties of the surface layer were varied depending upon the particular bituminous mixture that was being evaluated. For all mixtures, the properties of the base and the subgrade layers were kept the same.

Two different analyses were conducted. In the initial analysis, the materials data from the FAA study were used to predict the performance of a pavement with a rubber-modified asphalt concrete layer and a pavement with a conventional AC-10 asphalt surface layer. In the second analysis, the materials data from the FHWA study were used to predict the field performance of pavements constructed with different additive-modified asphalt concrete mixtures. Results from the analyses conducted are presented in the following.

Performance Evaluation of AC-10 and Asphalt-Rubber Concrete Mixtures.

Since resilient modulus, creep, fatigue, and repeated-load permanent deformation properties were determined at three different test temperatures in the FAA study, it was possible to evaluate pavement performance seasonally and thus achieve a more realistic simulation. Consequently, the following seasonal temperatures

were assumed in the analysis:

Season	Temperature °F
Winter	35
Spring	65
Summer	95
Fall	60

Material properties representative of each seasonal temperature were then determined from the laboratory data. For example, resilient moduli at each of the above temperatures were estimated using Figure 10, which shows the variation of modulus with test temperature for the AC-10 and asphalt-rubber concrete mixtures. It is emphasized that the performance predictions were made using available materials data on two specific asphalt mixtures. The performance comparisons presented in the following may change if other mixture designs are considered.

A comparison of the predicted fatigue performance of the conventional and rubber-modified asphalt concrete mixtures is shown in Figure 11. From this figure, better fatigue performance is expected from the asphalt-rubber mix than from the conventional AC-10 mix. Assuming, for example, a maximum allowable cracked area of 600 $ft^2/1000\ ft^2$, the asphalt-rubber mix is predicted to last about 14 years compared to about three years for the conventional mix of equivalent thickness. The longer fatigue life is consistent with the fatigue data determined from the laboratory. This information is presented in Appendix C. Thus, in areas where fatigue cracking is the predominant mode of distress, the use of asphalt rubber in pavement construction may be a viable alternative.

The increase in rut depth with cumulative load applications was predicted using the repeated-load permanent deformation data obtained from the laboratory. In the analysis, the permanent deformation parameters were adjusted to account for differences between the stresses expected in the field and the stresses under which the laboratory tests were performed. The adjustments involved calculation of stresses in a typical asphalt layer due to a 9000 pound single wheel load acting on top of the pavement section assumed in the performance evaluation.

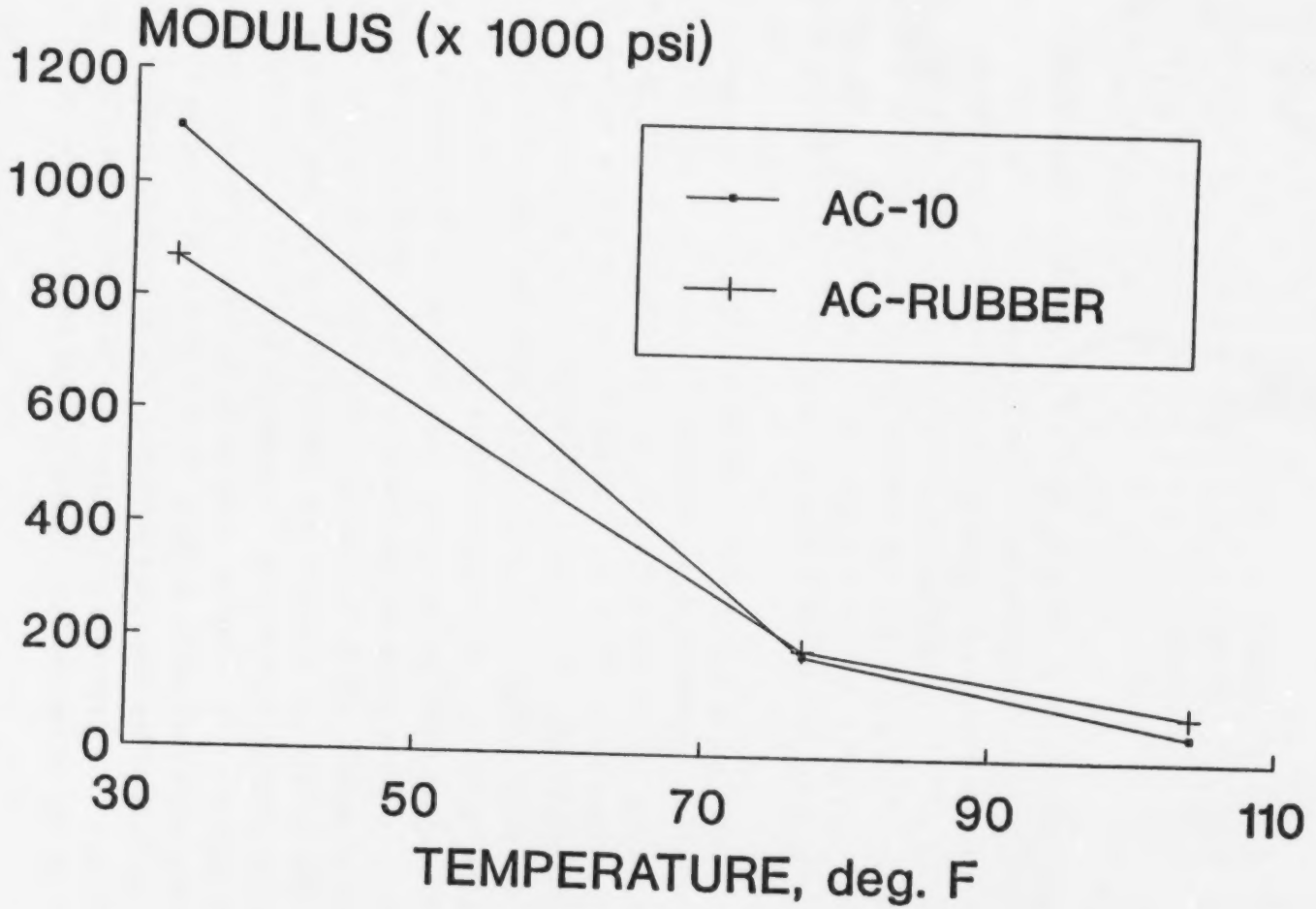


Figure 10. Variation of Diametral Resilient Modulus with Temperature for AC-10 and Asphalt-Rubber Concrete Mixtures.

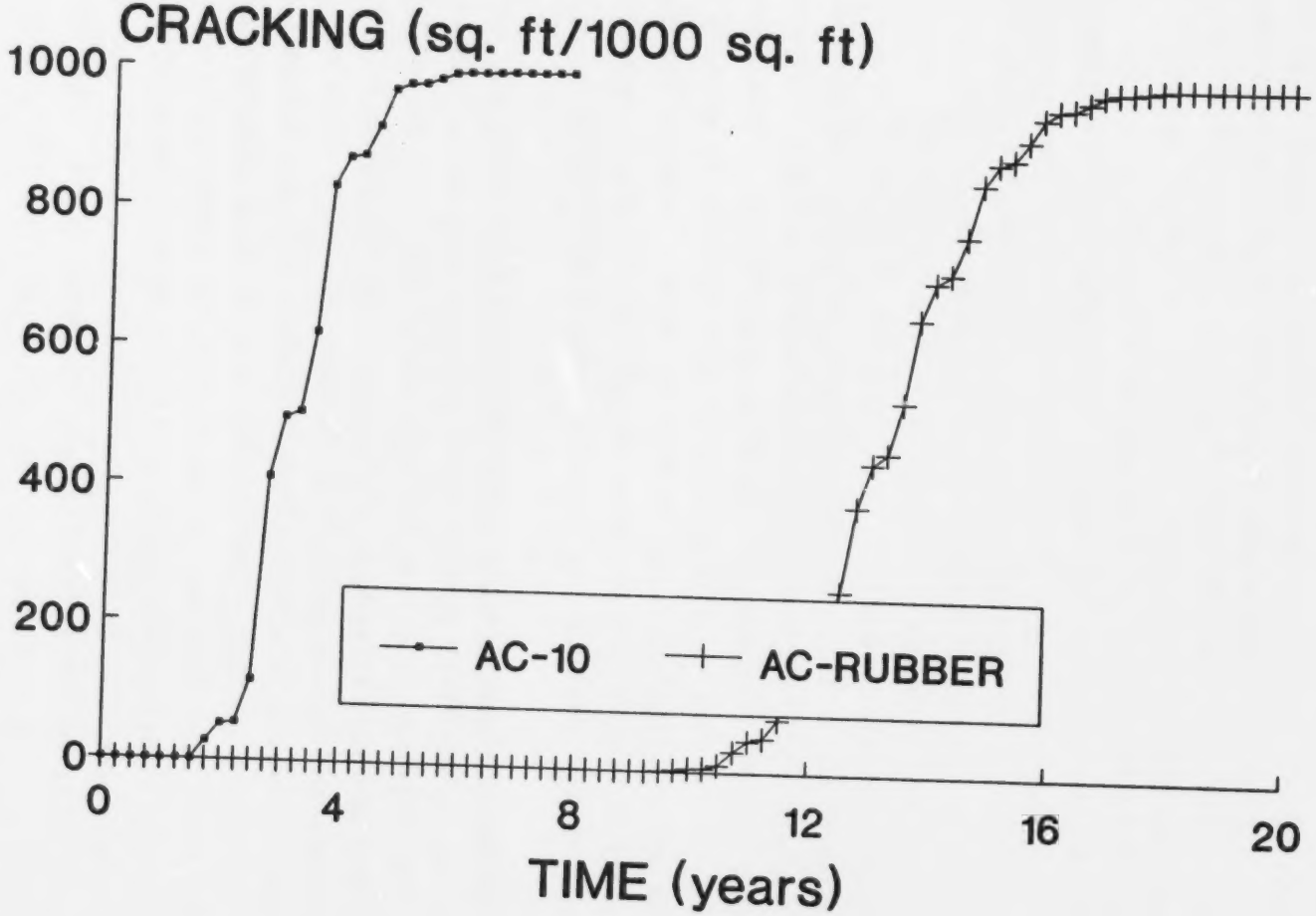


Figure 11. Comparison of Fatigue Performance of AC-10 and Asphalt-Rubber Concrete Mixtures.

Regression equations developed by Tseng and Lytton (26) were then used in conjunction with the predicted field stresses to get estimates of permanent deformation parameters representative of field conditions. These same equations were also used with the laboratory stresses under which the tests were conducted, and ratios of the permanent deformation parameters computed using field and laboratory stresses were determined. These ratios, which varied with temperature and depth within the asphalt layer, were then used as multipliers to the corresponding laboratory-determined permanent deformation parameters to get adjusted values for evaluation of pavement rutting.

Rut depth predictions obtained for both conventional and rubber-modified asphalt concrete mixtures are shown in Figure 12. The predicted curves are close to each other indicating that, on the basis of pavement rutting alone, no significant improvement in service life is achieved with the addition of rubber in the mix. For a maximum allowable rut depth of 0.5 inches, the predicted service life for both pavements is about 13 years, as estimated from Figure 12.

Based on the critical distress, however, the service life of the conventional asphalt concrete pavement is predicted to be governed by fatigue cracking, for which failure is expected to occur in three years. The asphalt-rubber pavement, on the other hand, is expected to fail initially by pavement rutting, with failure predicted to occur in about 13 years. Overall, therefore, the performance evaluation indicates that the addition of rubber in asphalt concrete mixtures has some potential for improving pavement performance.

Performance Comparisons of Asphalt Rubber and Other Additives. Performance predictions for different additive-modified asphalt concrete pavements were made using the materials data from the FHWA study (20). In the analysis, the predictions were made assuming an average year-round temperature of 70°F. It was not possible to evaluate pavement performance seasonally since repeated-load permanent deformation data for the asphalt mixtures evaluated were only available at a temperature of 70°F. The asphalts used in these mixtures came from a refinery in San Joaquin Valley, California (20). The conventional asphalt mix was made using an asphalt cement equivalent to an AC-20 while the additive-modified mixtures were made using an asphalt cement equivalent to an AC-5. Four different types of additives were investigated: 1) carbon black (Microfil); 2) thermoplastic block copolymer (Kraton); 3) polyethylene finely dispersed in

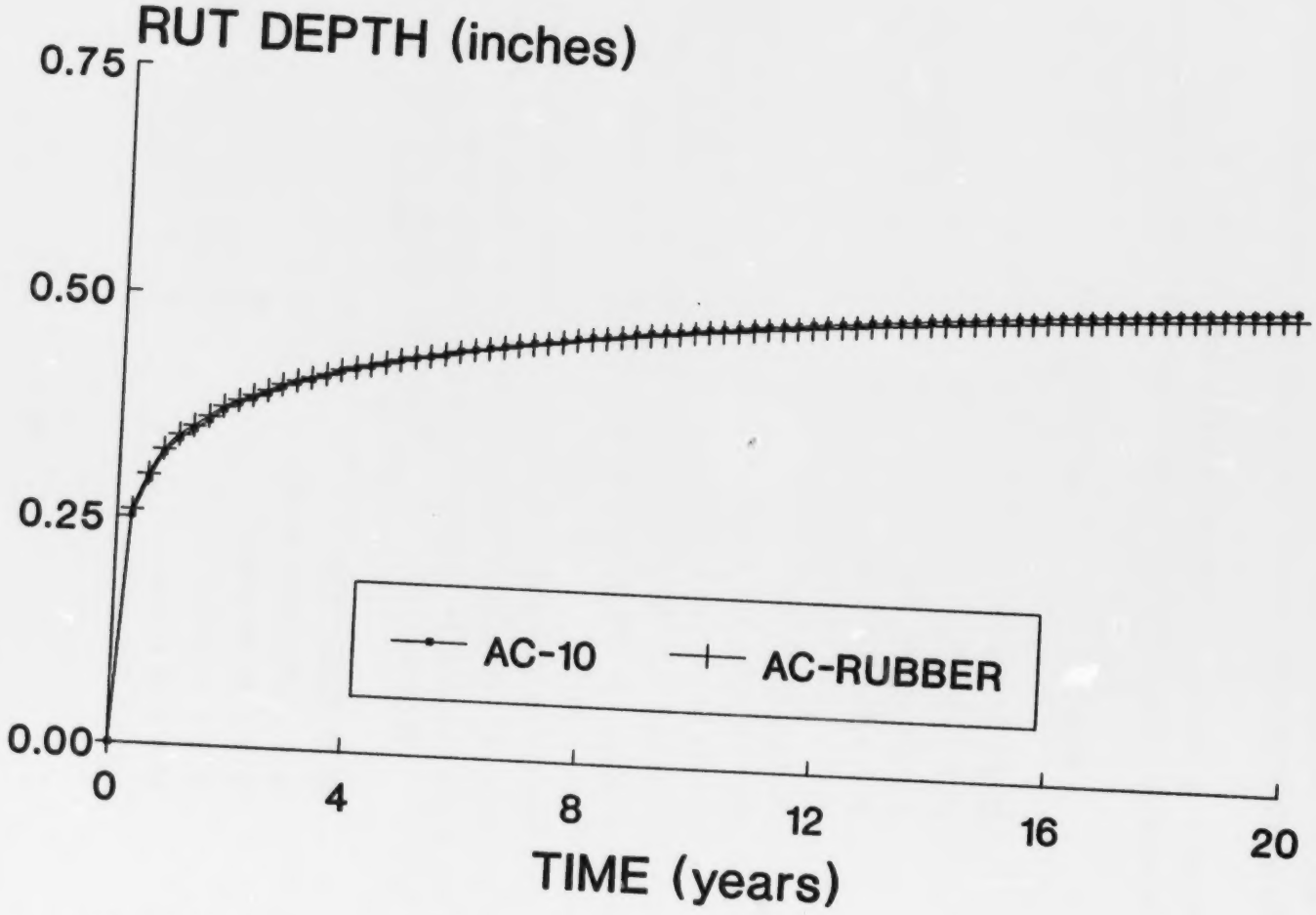


Figure 12. Comparison of Rut Depth Prediction for AC-10 and Asphalt-Rubber Concrete Mixtures.

asphalt (Novophalt); and 4) copolymers of ethylene and vinyl acetate (Elvax). The material properties of these mixtures are presented in Appendix C. Predictions of fatigue cracking for the different additives considered are shown in Figure 13. Also shown in the figure are the predicted curves for the AC-20 control mix and the asphalt-rubber mix. For consistency, fatigue performance of the asphalt-rubber mix was re-evaluated assuming a year-round temperature of 70°F.

Assuming a maximum allowable cracked area of 600 $ft^2/1000\ ft^2$, the following service lives are obtained from the predicted fatigue curves in Figure 13:

Material	Predicted Fatigue Life (years)
AC-5 + 5% Kraton	15
AC-5 + 5% Elvax	14
Asphalt-Rubber Mix	12
AC-5 + 5% Novophalt	8
AC-5 + 15% Carbon Black	< 1
AC-20 Control Mix	< 1

It is observed that the mixtures modified with the additives Kraton and Elvax gave the best performance in terms of fatigue life. It is also noted that the predicted fatigue life for the asphalt-rubber mix is relatively good. Of the mixtures evaluated, the AC-20 control mix and the carbon black mix gave the shortest fatigue lives.

With respect to pavement rutting, the performance predictions are summarized in Figure 14. Assuming a maximum allowable rut depth of 0.5 inches, the following predicted service lives are obtained from Figure 14:

Material	Predicted Life to 0.5-inch Rutting (years)
AC-20 Control Mix	> 20
AC-5 + 15% Carbon Black	> 20
AC-5 + 5% Novophalt	16
AC-5 + 5% Elvax	8
AC-5 + 5% Kraton	4
Asphalt-Rubber Mix	3

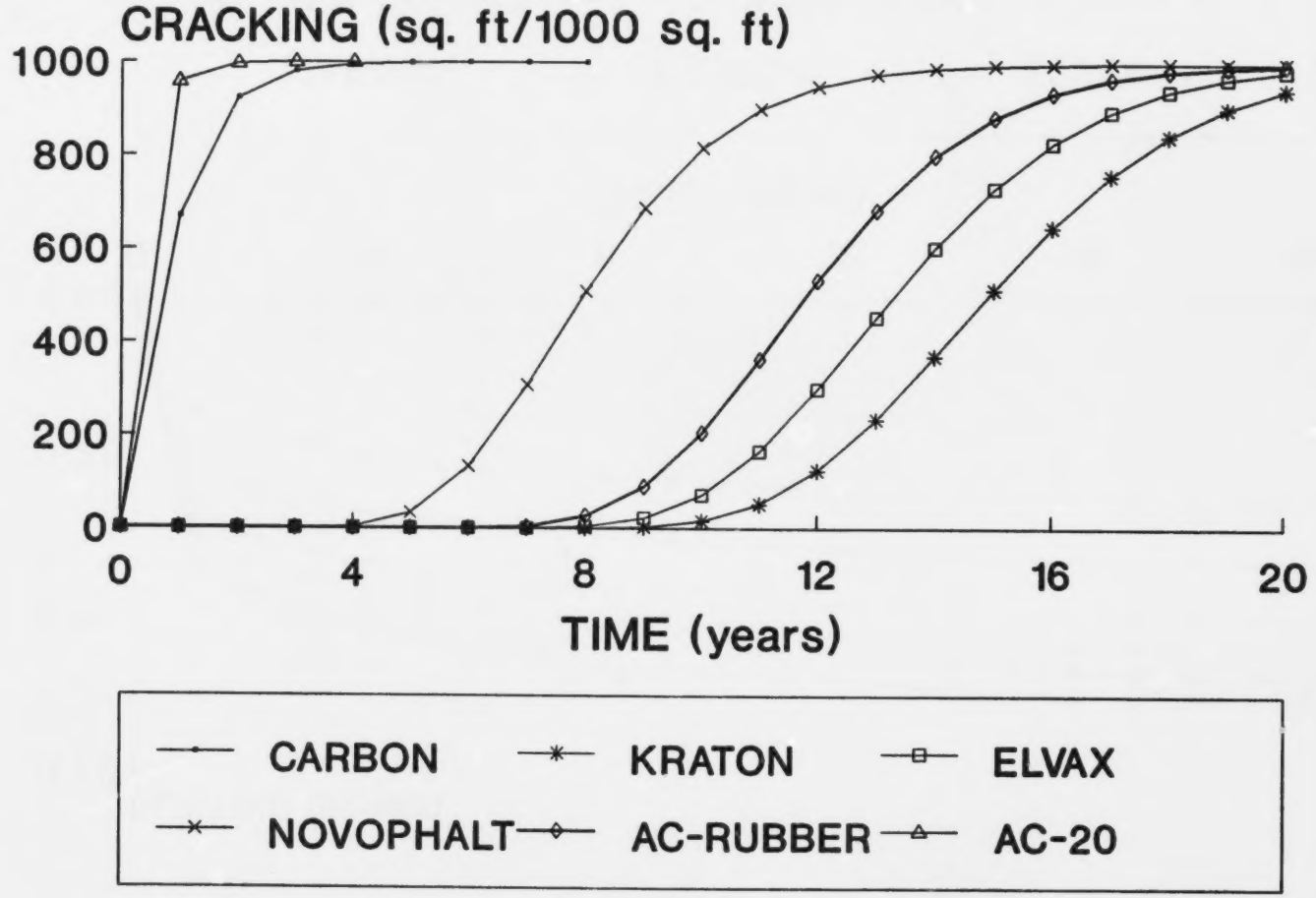


Figure 13. Predicted Fatigue Performance of San Joaquin Valley and Rubber-Modified Asphalt Mixtures.

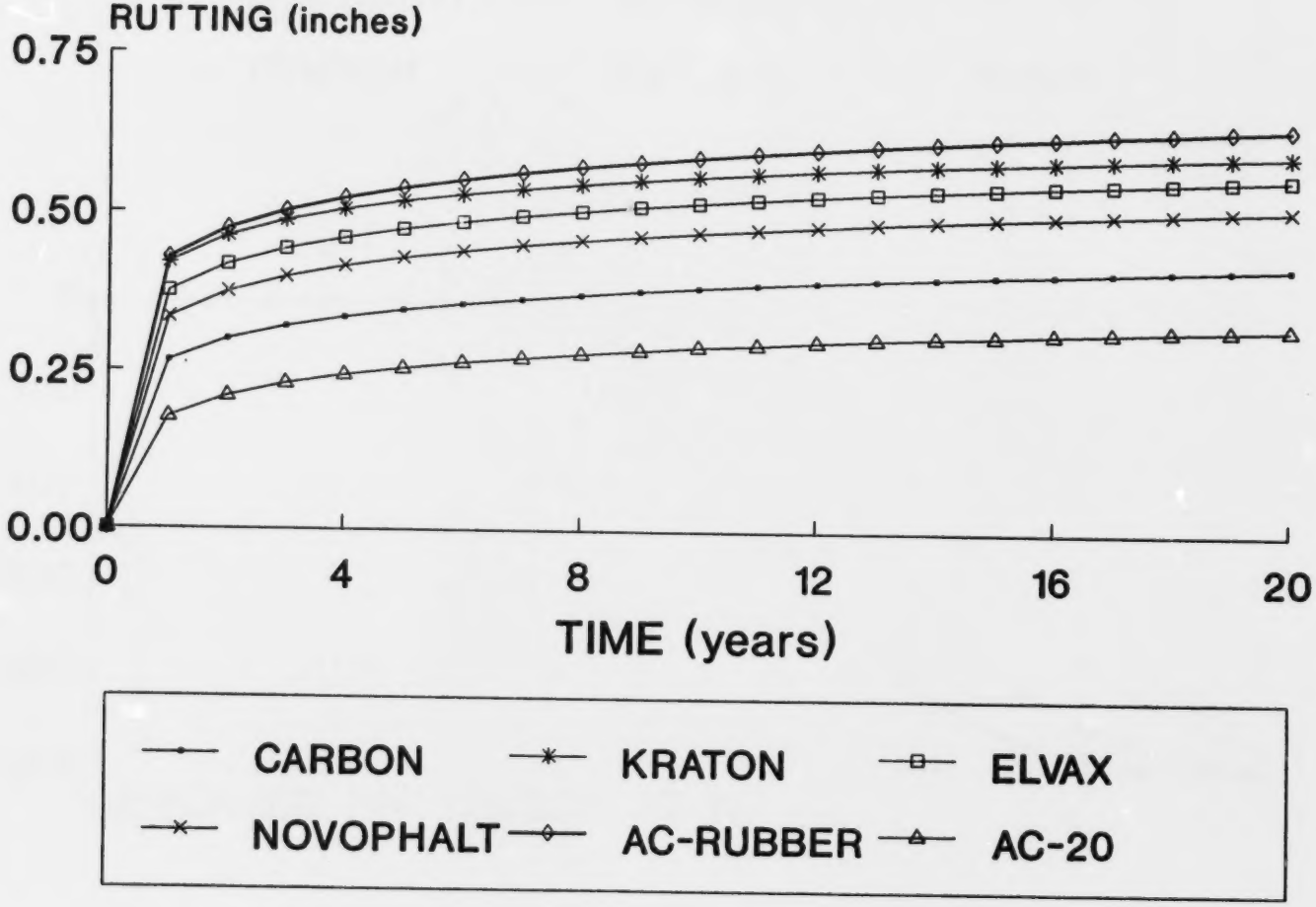


Figure 14. Rut-Depth Predictions for San Joaquin Valley and Rubber-Modified Asphalt Mixtures.

It is observed that, whereas the AC-20 control and carbon black mixtures gave the shortest fatigue lives, both mixtures are predicted to have the best performance in terms of pavement rutting. Thus, in areas where rutting is the predominant mode of distress, such as in hot or warm climatic regions or where aggregate quality is poor, these binders may be appropriate to use. This result points out a benefit of having rational models for evaluating pavement performance. Through application of these models the pavement engineer is able to identify paving materials that are the most appropriate for the conditions in the locality of interest, and thus is able to optimize pavement design.

It is also noted that the asphalt-rubber mix did not perform well in terms of pavement rutting. On the basis of this distress mode, the predicted service life is only three years. This value is much less than that obtained in the previous analysis, the reason being that the performance evaluation conducted herein assumed a year-round temperature of 70°F. In the previous case, the performance was evaluated seasonally for which the assumed temperatures were below 70°F for three quarters of the year. In view of the fact that permanent deformation increases with pavement temperature, the assumption of a year-round temperature of 70°F was probably too conservative. However, the analysis was constrained by the available data on repeated-load permanent deformation properties for the San Joaquin Valley asphalt mixtures. Consequently, for consistency in the performance comparisons of asphalt rubber and additive-modified mixtures, the performance predictions for the asphalt-rubber mix, at an assumed year-round temperature of 70°F, were used.

COST-EFFECTIVENESS OF ASPHALT-RUBBER CONCRETE PAVEMENTS

In order to evaluate the potential cost-effectiveness of asphalt-rubber concrete pavements, approximate in-place costs for the different materials evaluated were estimated. The cost estimates are given in Table 5. The cost figures given for the AC-10 and AC-20 asphalt concrete mixtures are considered to be representative of current in-place costs of conventional asphalt concrete mixtures. The cost for an asphalt-rubber mixture of $52/ton was based on an actual paving project in Amarillo that was scheduled for construction in August 1990. For the additives, a uniform cost of $36/ton was established on the basis of cost data presented by Button in Reference 27. The cost data obtained from

Table 5. Approximate In-Place Costs for Asphalt Concrete Mixtures.

Material	Approximate In-Place Cost, $/ton	Density, lbs/ft^3	Tons/sq. yard	Approximate In-Place Cost, $/yd^2
AC-10 Control Mix	32	151	0.340	10.87
Asphalt-Rubber	52	145	0.326	16.97
AC-20 Control Mix	30	141	0.317	9.52
AC-5 + 15% Carbon Black	36	141	0.317	11.42
AC-5 + 5% Kraton	36	141	0.317	11.42
AC-5 + 5% Novophalt	36	141	0.317	11.42
AC-5 + 5% Elvax	36	141	0.317	11.42

Reference 27 were adjusted to get costs that were consistent with the actual dosages of additives used in the FHWA study and to include an approximate cost for pre-blending of additive with asphalt. The cost of $36/ton represents a $6/ton increase over the price of the conventional AC-20 control mix. This is within the range of the expected increase in paving cost with the use of additives, estimated by Little et al. to be from $4/ton to $9/ton (20).

Using the approximate costs given and the performance predictions presented previously, a measure of the cost-effectiveness of each material was obtained by calculating the equivalent uniform annual cost of construction. This is defined as the cost which, if paid annually over the life of a given pavement, will be equivalent to the initial construction cost. The formula for equivalent uniform annual cost is:

$$A = \frac{P\,[i * (1 + i)^n]}{[(1 + i)^n - 1]}$$

where,

A = equivalent uniform annual cost
P = initial construction cost
i = interest rate
n = pavement life in years

It is realized that cost-effectiveness is also influenced by maintenance and user costs. However, very little data exist for estimating these costs for asphalt-rubber and additive-modified pavements. Consequently, only the initial construction cost was considered in evaluating cost-effectiveness. Comparisons of the equivalent annual costs of the different mixtures evaluated are presented in the following subsections.

Cost-Effectiveness of AC-10 and Asphalt-Rubber Concrete Mixtures

Table 6 summarizes the equivalent uniform annual costs for AC-10 and asphalt-rubber concrete mixtures that are based on performance predictions utilizing materials data from the FAA study. In calculating annual costs, an effective interest rate of four percent was assumed. This was considered to be

Table 6. Equivalent Uniform Annual Costs for AC-10 and Asphalt-Rubber Concrete Mixtures.

Material	Approximate In-Place Cost ($/yd^2)	Predicted Service Life (years)		Equivalent Uniform Annual Cost ($/yd^2)	
		Fatigue[a]	Rutting[b]	Fatigue	Rutting
AC-10 Control Mix	10.87	3	13	3.92	1.09
Asphalt-Rubber	16.97	14	13	1.61	1.70

[a]Service life prior to 600 ft^2/100 ft^2 of cracking.
[b]Service life prior to 0.5-inch rutting.

a reasonable estimate of the difference in the actual interest and actual inflation rates as applied to construction.

From Table 6, it is observed that, in terms of fatigue cracking, the asphalt-rubber mix is more cost-effective than the AC-10 mix. Thus, even though a square yard of the material costs about $6 more than a square yard of the conventional mix, the substantial improvement in fatigue life (14 years versus three years for AC-10) makes it a better alternative on the basis of a lower equivalent uniform annual cost of construction. This suggests that, in areas where fatigue cracking is the predominant mode of distress, the asphalt-rubber mix may be a viable alternative to conventional asphalt mixtures.

In terms of pavement rutting, the results indicate that the conventional AC-10 mix is the more cost-effective alternative. As noted previously, the predictions did not show any significant difference in the rutting performance of both AC-10 and asphalt-rubber concrete pavements. This indicates that, in areas where rutting is the primary mode of distress, conventional asphalt mixtures may be more appropriate to use than asphalt-rubber mixtures.

However, based on the critical distress, the asphalt-rubber mix is more cost-effective than the AC-10 mix. In this particular case, the AC-10 mix is predicted to fail initially in three years by fatigue cracking; whereas, the asphalt-rubber mix is expected to fail initially in 13 years by rutting. The corresponding annual costs from Table 6 are $3.92/yd^2 and $1.70/yd^2, for AC-10 and asphalt-rubber concrete mixtures, respectively.

Cost-Effectiveness of Additive-Modified Mixtures

The equivalent uniform annual costs for the additive-modified mixtures are summarized in Table 7. In terms of fatigue cracking, the Kraton and Elvax-modified asphalt mixtures were the most cost-effective. In addition, the results indicate that the cost of asphalt-rubber has to come down in order for it to be more competitive. This is indicated in the lower annual cost calculated for the Novophalt-modified asphalt mix ($1.70/yd^2) than the asphalt-rubber mix ($1.81/yd^2) even though the fatigue life of the latter is predicted to be four years greater than that of the former.

In terms of pavement rutting, the most cost-effective mixtures are the AC-20 control mix and the carbon black mix. Pavements with these mixtures were

Table 7. Equivalent Uniform Annual Costs for San Joaquin Valley and Asphalt-Rubber Concrete Mixtures.

Material	Approximate In-Place Costs ($/yd^2)	Predicted Service Life (years)		Equivalent Uniform Annual Cost ($/yd^2)	
		Fatigue[a]	Rutting[b]	Fatigue	Rutting
AC-20 Control Mix	9.52	<1	>20	9.52	0.70[c]
AC-5 + 15% Carbon Black	11.42	<1	>20	11.42	0.84[c]
AC-5 + 5% Kraton	11.42	15	4	1.03	3.15
AC-5 + 5% Novophalt	11.42	8	16	1.70	0.98
AC-5 + 5% Elvax	11.42	14	8	1.08	1.70
Asphalt-Rubber Mix	16.97	12	3	1.81	6.12

[a] Service life prior to 600 ft^2/1000 ft^2 of cracking.

[b] Service life prior to 0.5-inch rutting.

[c] Cost based on 20 year service life.

predicted to develop less than 0.5-inch rutting at the end of the 20-year design period. Since the annual costs for these mixtures were calculated based on a 20-year service life, the estimates shown in Table 7 would have been even lower had the performance evaluation been continued past the end of the 20-year design period. The asphalt-rubber mix was the least cost-effective alternative on the basis of pavement rutting. Its predicted service life was the shortest among the mixtures evaluated, and it also was the most expensive. Thus, in areas where rutting is the primary mode of distress and fatigue cracking is not a problem, asphalt-rubber concrete mixtures may not be economical to use.

On the basis of the critical distress, the most cost-effective pavements were those constructed with Novophalt and Elvax-modified asphalt concrete mixtures. Both of these pavements were predicted to fail initially in eight years, with the Novophalt mix failing by fatigue cracking, and the Elvax mix failing by rutting. The equivalent uniform annual cost, based on the critical distress, is $\$1.70/yd^2$ for both mixtures. Thus, in areas where fatigue cracking and rutting are equally predominant, the use of Novophalt or Elvax-modified asphalt concrete mixtures may be the most economical.

SUMMARY

Based on the evaluation presented in this chapter, the following comments are forwarded:

1. Results indicate that the fatigue performance of asphalt concrete mixtures is significantly improved with the addition of rubber. Thus, in areas where fatigue cracking is anticipated to be the primary mode of distress, asphalt rubber may be a cost-effective alternative, and thus, should be considered in the selection of materials for pavement design and construction.
2. Compared with additive-modified mixtures in terms of both fatigue cracking and rutting, the expected performance of asphalt rubber, needs to improve and the cost reduced in order for it to be more competitive with the additive-modified mixtures, in particular, Kraton, Elvax, and Novophalt. On the basis of the FAA study (19), the major component of the in-place cost is the cost of the asphalt-

rubber binder itself. This cost may range from 41 to 45 percent of the in-place cost depending on the binder content.

3. The evaluation of cost-effectiveness included only initial construction cost. It should be recognized that the computed cost figures may change if other cost items, such as maintenance and user costs, are considered. It was not possible to include these costs in the economic analysis due to the absence of maintenance and user cost information for asphalt rubber and additive-modified pavements.

4. The computed cost figures for asphalt rubber may also change if certain intangibles are considered in the economic analysis. Reported benefits (28) include the benefit to the environment of eliminating a solid waste product, the potential benefit of reduced traffic noise from asphalt-rubber pavements, and potential improvement in safety due to improved skid resistance. The analysis herein was primarily concerned with evaluating cost-effectiveness on the basis of expected pavement performance.

REFERENCES

1. "ATR Develops Scrap Tire Recycling Process," Elastomerics, (U.S. ISSN 0146-0706) Communications Channels, Inc., 6255 Barfield Road, Atlanta, Georgia, July, 1989.
2. Epps, J. A. "Seminar Summary," Proceedings, National Seminar on Asphalt Rubber, San Antonio, Texas, October, 1981.
3. Shuler, T. S., Pavlovich, R. D., Epps, J. A., and Adams C. K. "Investigation of Materials and Structural Properties of Asphalt-Rubber Paving Mixtures," Research Report RF 4811-1F, Texas Transportation Institute, Texas A&M University, College Station, Texas, September, 1985.
4. Schofield, L. A., "The History, Development, and Performance of Asphalt Rubber at ADOT," Arizona Transportation Research Center, 1989.
5. Shuler, T. S., Gallaway, B. M. and Epps, J. A., "Evaluation of Asphalt-Rubber Membrane Field Performance," Research Report 287-2, Texas Transportation Institute, Texas A&M University, College Station, Texas, May, 1982.
6. Letter from Joe M. Battle, Texas SDHPT District Engineer in El Paso, to Cindy Estakhri, Texas Transportation Institute, June 12, 1990.
7. Jacobson, C. C. and Schnormeier, R. H., "Cost Effectiveness of Asphalt Rubber," Asphalt Rubber Producer's Group, Proceedings of National Seminar on Asphalt Rubber, Kansas City, Missouri, 1989.
8. Morris, G. R. and McDonald C. H., "Asphalt-Rubber Stress-Absorbing Membranes: Field Performance and State of the Art," Transportation Research Record No. 595, 1976.
9. Adams, C. K. and Gonzales, J., "Asphalt-Rubber Interlayer Field Performance," Research Report 449-1F, Texas Transportation Institute, Texas A&M University, College Station, Texas, June, 1987.
10. Chehovits, J. G., "Design Methods for Hot-Mixed Asphalt-Rubber Concrete Paving Materials," Proceedings, National Seminar on Asphalt-Rubber, Kansas City, Missouri, 1989, pp. 151-190.
11. McQuillen Jr., J. L., Takallou, H. B., Hicks, R. G., and Esch, D., "Economic Analysis of Rubber-Modified Asphalt Mixes," ASCE Journal of Transportation Engineering, Vol. 114, No. 3, May 1988, pp. 259-277.

12. Schofield, L., "The History, Development, and Performance of Asphalt Rubber at ADOT," Proceedings, National Seminar on Asphalt Rubber, Kansas City, Missouri, 1989, pp. 328-365.
13. Van Kirk, J. L., "CALTRANS Experience With Asphalt-Rubber Concrete - An Overview and Future Direction," Proceedings, National Seminar on Asphalt Rubber, Kansas City, Missouri, 1989, pp. 417-431.
14. Larsen, D. A., "Eight-Year Performance Evaluation of an Asphalt-Rubber Hot-Mix Pavement," Proceedings, National Seminar on Asphalt Rubber, Kansas City, Missouri, 1989, pp. 536-556.
15. Roberts, F. L., Kandhal, P. S., Brown, E. R., and Dunning, R. L., "Investigation and Evaluation of Ground Tire Rubber in Hot-Mix Asphalt," National Center for Asphalt Technology, Auburn University, Alabama, 1989.
16. Page, G. C., "Florida's Experience Utilizing Ground Tire Rubber in Asphalt Concrete Mixtures," Proceedings, National Seminar on Asphalt Rubber, Kansas City, Missouri, 1989, pp. 499-535.
17. Turgeon, C. M., "The Use of Asphalt-Rubber Products in Minnesota," Proceedings, National Seminar on Asphalt Rubber, Kansas City, Missouri, 1989, pp. 311-327.
18. Solberg, C. E., and Lyford, D. L., "Recycling With Asphalt Rubber," Proceedings, National Seminar on Asphalt Rubber, Kansas City, Missouri, 1989, pp. 486-498.
19. Hoyt, D. M., Lytton, R. L., and Roberts, F. L., "Criteria for Asphalt-Rubber Concrete in Civil Airport Pavements: Vol II - Evaluation of Asphalt-Rubber Concrete," Report No. DOT/FAA/PM-86/39, II, Federal Aviation Administration, Washington, D. C., 1987.
20. Little, D. N., Button, J. W., White, R. M., Ensley, E. K., Kim, Y., and Ahmed, S. J., "Investigation of Asphalt Additives," Report No. FHWA/RD-87/001, Federal Highway Administration, McLean, Virginia, 1986.
21. Tseng, K., "A Finite Element Method for the Performance Analysis of Flexible Pavements," PhD. Dissertation, Texas A&M University, College Station, Texas, 1988.
22. Tseng, K., and Lytton, R. L., "Fatigue Damage Properties of Asphaltic Concrete Pavements," paper presented at the 69th Annual Meeting of the Transportation Research Board, Washington, D. C., 1990.

23. Yandell, W. O., and Lytton, R. L., "Residual Stresses Due to Traveling Loads and Reflection Cracking," Report No. FHWA/TX-79-207-6, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1979.
24. Yandell, W. O., and Lytton, R. L., "The Effect of Residual Stress and Strain Build-Up in a Flexible Pavement by Repeated Rolling of a Tire," Report RF4087-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1979.
25. Balbissi, A. H., "A Comparative Analysis of the Fracture and Fatigue Properties of Asphalt Concrete and Sulphlex," PhD. Dissertation, Texas A&M University, College Station, Texas, 1983.
26. Tseng, K., and Lytton, R. L., "Prediction of Permanent Deformation in Flexible Pavement Materials," paper presented at the ASTM Symposium on Implication of Aggregates in the Design, Construction, and Performance of Flexible Pavements, New Orleans, Louisiana, 1986.
27. Button, J. W., "Asphalt Additives in Highway Construction," Research Report 187-14, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1988.
28. McQuillen Jr., J. L., Takallou, H. B., Hicks, R. G., and Esch, D., "Economic Analysis of Rubber-Modified Asphalt Mixes," ASCE Journal of Transportation Engineering, Vol. 114, No. 3, May 1988, pp. 259-277.
29. "Texas Asphalt-Rubber Survey," Asphalt Rubber Producers Group, 3336 North 32nd Street, Suite 106, Phoenix Arizona.

APPENDIX A

OTHER USES OF SCRAP TIRES

APPENDIX A
OTHER USES OF SCRAP TIRES

INTRODUCTION

The subject of discarded material in this country is a growing concern. Solutions to remedy the problem are being sought as never before. One of our leading exports in tonnage is scrap. The proliferation of waste stockpiles must be dealt with to reduce the cost of storage, to reduce the public outcry, and to improve the condition of our environment. Aside from the problem of what to do with waste, the biggest immediate problem with waste is the separation, collection, and storage requirements. Safe disposal of waste tires is not a simple task. A tire is a highly engineered composite product that cannot be recycled like paper or glass. Even the tire manufacturers are not interested in them because they want new rubber for their tires. When faced with the fact that approximately two billion tires are stockpiled and two hundred million waste tires are produced each year in the U. S., it is evident that some long-term answers are needed.

Scrap tire disposal can be difficult and stockpiles may be hazardous. Many are stored above ground because the tires have a tendency to rise to the surface if they are placed in landfills. But when stored above ground they become full of stagnant water which provides a haven for disease carrying insects and other vermin. The most obvious hazard in stockpiles is the potential for fire. In 1984, a 1.5 million tire stockpile caught fire and burned out of control for seven months (A1). The fire left five acres of ash and metals containing hazardous waste (zinc) which proved to be extremely difficult to clean up by conventional methods.

Materials that make up tires pose unique problems and require unique solutions. Recently much experimentation in the area of utilization of these products has produced some promising findings. Companies are now developing methods of converting waste tires into reusable rubber carbon black and steel and fuel for steam or power generation. Historically, the financial incentives for recycling efforts have not been great enough to make the processing requirements worthwhile, but more recently findings from new research and development have shown improved economics. Some uses for scrap tires other than asphalt rubber

are categorized and discussed below.

PAVEMENTS

Numerous noise level studies in the United States and abroad indicate the use of asphalt rubber as binder in hot-mixed asphalt concrete significantly reduces traffic noise level. Open-graded asphalt hot-mix containing crumb rubber from tires has reduced noise levels 50 to 85 percent. This represents a reduction in traffic speed of about 25 percent or a doubling of the distance from the noise source. Open graded designs without rubber can reduce noise level by up to 50 percent. By comparison, sound walls cost more than $400 per linear foot; whereas, asphalt-rubber hot-mix overlays cost about $12 per linear foot per lane per inch (A2).

Many northeastern Arizona highways are built on expansive clay which often shortens pavement service life and occasionally produces hazardous driving conditions. Impermeable asphalt-rubber membranes have been used there to control moisture in the clay subgrades (A3). The membrane reduces evapotranspiration of moisture from the subgrade and infiltration of moisture from surface runoff. Field observations plus objective measurements indicate that the membrane treatment has improved pavement performance (reduced cracking and extension of good ride quality).

In Minnesota, waste tires have been shredded into 6 to 8-inch pieces that are used in stabilizing poor subgrades in marshy areas. A layer of these rubber chips on top of the subgrade "supposedly keeps the road from sinking" (A4). The layer provides separation to keep the base and subgrade materials from mixing, increases tensile strength at the bottom of the base layer, and improves the load spreading ability of the base. Results from these tests will be forthcoming from the Minnesota Department of Natural Resources.

FUEL

Perhaps the most important development to offer disposal of large volumes of whole scrap tires is energy conversion. Given the average tire weighs approximately 20 lbs and has a heating value of 15,000 BTU/lb it makes sense to extract the fuel value. Firestone Tire and Rubber Company's batch type incineration/heat recovery steam generators will burn whole tires, waste rubber,

wood, paper, and waste oils at a substantial volume (A5, A6). One system such as this produces 23,000 lb/hr of 240 psia/400°F steam. The problems related to this process such as feeding whole or shredded tires and the emissions produced have been resolved. Different combustion processes and secondary combustion has been implemented to enhance the system and reduce combustion by-products. At the end of the furnace hearth the nonhazardous ash and non-combustibles are removed mechanically. Only minor air pollution control is necessary if combustion temperatures are controlled to reduce smoke and NO_x formation. Depending upon the fuel burned and the combustion conditions, the degree of fouling and subsequent drop in efficiency dictates the duration of continuous operation. Plans must be considered to provide an adequate and consistent supply of fuel once local tire stockpiles have been depleted.

Another example of the tire to energy alternative has been constructed near Modesto, California at the largest single waste tire collection site in the U.S. The Oxford Energy Company of New York, N.Y. and General Electric Company are operating a 14-MW power producing plant that burns 4.5 million tires/yr (A7, A8). This plant is designed to accept 6 foot diameter tires along with a special apparatus for controlling the sticky tars produced during combustion and eliminating slag adhering to the surfaces. The emissions control include fabric filters, a wet scrubber with lime to absorb SO_2, and a NO_x removal system. This is a dual unit designed to produce 130,000 lb/hr of 930-psia/930°F steam to drive a single turbine-generator.

The Oxford Energy Company has made serious commitment to engage in the collection and shredding of waste tires. Their tire recycling facility in Bloomfield County has a processing capacity of five million waste tires per year. Oxford estimates that two 40 MW plants along with their recycling facility would consume 67 percent of New England's waste-tire production.

Construction of the largest scrap tire-to-energy power plant in the world has begun near of El Monte, California which has strict emission requirements (A9). They claim to have tested a process where less emissions per kilowatt are emitted than a coal-fired power plant. Ashes from rubber tires are being used as filler in concrete pipe and other products.

Experiments at Argonne National Laboratory, near Chicago, have shown a substantial cost savings when shredded tire rubber is mixed with high-sulphur

coal as a fuel supplement.

A papermill in Tomahawks, Wisconsin uses the shredded waste tires to supplement its coalburning facility (A10).

ASPHALT AND FUEL PRODUCTION

The New Paraho Corporation of Denver, Colorado has initiated a program to investigate the feasibility of producing high quality asphalt and fuels from the pyrolysis (destructive distillation) of oil shale with five percent spent automobile tires. The concept is to market the asphalt as an additive to improve the properties, particularly moisture susceptibility, of standard petroleum-based asphalts and thereby make the process cost-effective.

Tests at their pilot plant revealed that, from an overall operability and plant performance standpoint, there were no differences between the operations with and without five percent tire chips in the oil shale. From a retort point of view, operations were actually improved by the tires. In addition, the heating value of the product gas produced from the coprocessed material was approximately 20 percent higher than normal, owing to the higher weight percentage of hydrogen and hydrocarbons present in the product gas from the coprocessed material in comparison to the typical product gas produced from 100 percent shale operations.

The potential benefits associated with the coprocessing of spent tires with oil shale include the relatively high oil content of tires per unit weight in comparison to oil shale and the higher percentage of naphtha (gasoline), making this oil more valuable as a refinery feedstock. Whether or not the use of this coprocessed material will affect the properties of the asphalt has yet to be established. If the process appears profitable and the full-scale plant is built to utilize 5 percent tires, it will consume most of the scrap tires produced in the state of Colorado.

BUILDING PRODUCTS

Rubber Research Elastomeric of Minneapolis produces a product called Tirecycle, made from shredded waste tires and new rubber, for use in automobile truckliners, floor mats, and dashboards (A11).

Another waste tire recycling process now underway is called "reclassification" and involves shredding, pyrolysis (melting), and purifying

tire components and results in by-products of carbon black, oil, and gas. The by-products of this process are to be sold to the automotive and general industrial rubber goods industries. This is a patented commercial process developed by American Tire Reclamation, Inc. This company has plants in Oregon, Ohio, and Pennsylvania each of which are expected to process 5,000 tires per day. There is not much waste residue from this process and it can be landfilled with no danger to the environment.

Tests are in progress on a variety of products using reclaimed shredded rubber such as containers, plants, fence posts, and domestic drain pipe. J & J Trading, Inc., of Chester, Pennsylvania claims that the shredded rubber is cheaper than any raw material used in manufacturing drain and sewer pipes (A12).

EROSION

Discarded tires have been used in various applications to control erosion, they have been simply placed in the bottom of drainage ditches where silt and grass eventually conceal them to hide their unsightly appearance. Tires have also been lashed together using steel cable to form a large mesh-like network and fastened to almost vertical stream banks or slopes to prevent undercutting or loss of bank soil, respectively. Although this function for used tires may find application in the Department, it is not likely a high-volume usage.

ARTIFICIAL REEFS

Scrap tires have been used by ocean engineers to build artificial reefs to provide homes for all sorts of aquatic life. These large contrivances may require hundreds of thousands of tires which are usually fastened together with steel or plastic rope. Artificial reefs are labor intensive and, therefore, quite expensive to construct. It will likely be difficult to find funding for such endeavors.

REFERENCES

A1. "Tire Fire Cleanup to Get Rolling,"Civil Engineering (U.S. ISSN 0885-7024), American Society of Civil Engineers, 345 East 47th Street, New York, New York, January, 1989.

A2. "Noise Reduction with Asphalt Rubber," The Rebounder, Vol. 6, No. 3, Asphalt Rubber Producers Group, 3336 North 32nd Street, Suite 106, Phoenix, Arizona, Summer, 1990.

A3. Forstie, D., Walsh, H., and Way, G., "Membrane Technique for Control of Expansive Clays," Transportation Research Board, Washington, D.C., 1979.

A4. "Minnesota Cleans Up Waste Tire Dumps," Elastomerics (U.S. ISSN 0146-0706), Communications Channels, Inc., 6255 Barfield Road, Atlanta, Georgia, March, 1989.

A5. Makansi, K., "Firestone to Burn Scrap Tires to Make New Ones," Power, (U.S. ISSN 0032-5929), McGraw-Hill Publications Co., 11 West 19th Street, New York, New York, June 1982.

A6. Makansi, K., "Plant Converts Tires, Steam to Steam Fairly Successfully," Power (U.S. ISSN 0032-5929), McGraw-Hill Publications Co., 11 West 19th Street, New York, New York, June, 1986.

A7. Makansi, K., "Developments to Watch," Power (U.S. ISSN 0032-5929), McGraw-Hill Publications Co., 11 West 19th Street, New York, New York, April, 1987.

A8. Ballman, B., and Spalding, B. J., "New Uses for Old Tires that Pay," Chemical Week (U.S. ISSN 0009-272X), Chemical Week Associates, 810 Seventh Avenue, New York, New York, December 2, 1987.

A9. "Rialto Power Issued Permits for Scrap Tire Facility," Alternative Sources of Energy (U.S. ISSN 0146-1001), Alternative Sources of Energy Inc., 107 South Central Avenue, Milaca, Minnesota, 1990.

A10. "Wisconsin Adds Tires to Asphalt Paving Mix," Civil Engineering (U. S. ISSN 0885-7024), American Society of Civil Engineers, 345 East 47th Street, New York, New York, 1988.

A11. "Recycled Rubber Tires Basis for New Products," Engineering News Record, January 19, 1989.

A12. "ATR Develops Scrap Tire Recycling Process," Elastomerics (U.S. ISSN 0146-0706), Communications Channels, Inc., 6255 Barfield Road, Atlanta, Georgia, July, 1989.

APPENDIX B

BID PRICES FOR CHIP SEALS

Table B1. Bid Prices for Grade 4 Chip Seals in 1989.

		Job Size		In-Place Cost
Binder Type	Location	Lane Miles	Sq. Yd.	Per sq. yd.
AC	Dist 24 Presidio Co.	373	2.6×10^6	$ .55
	Dist 3 Wichita Co.	620	4.4×10^6	$ .42
				Weighted avg. $.47
AC W/Latex	Dist 4 Ochiltree Co.	713	5.0×10^6	$ .52
	Dist 4 Deaf Smith Co.	494	3.5×10^6	$ .49
	Dist 5 Bailey Co.	1385	9.8×10^6	$ .48
	Dist 7 Runnels Co.	785	5.5×10^6	$ .49
	Dist 7 Val Verde Co.	530	3.7×10^6	$ .49
	Dist 15 Frio Co.	572	4.0×10^6	$ .44
	Dist 16 Live Oak Co.	908	6.4×10^6	$ .46
				Weighted avg. $.48
Emulsion	Dist 23 Mills Co.	423	3.0×10^6	$ .50
	Dist 23 Eastland Co.	457	3.2×10^6	$ .46
				Weighted avg. $.48
Emulsion W/P	Dist 17 Grimes Co.	262	1.8×10^6	$ .56
Asphalt Rubber	Dist 24 Presidio Co.	291	2.1×10^6	$1.14

APPENDIX C

MATERIALS INFORMATION FOR EVALUATING ASPHALT-RUBBER CONCRETE MIXTURES

APPENDIX C

MATERIALS INFORMATION FOR EVALUATING ASPHALT-RUBBER CONCRETE MIXTURES

Available data from the literature on material properties of asphalt-rubber mixtures were used to predict the field performance of asphalt-rubber pavements. In the performance evaluation, the asphalt-rubber mix was compared to conventional and additive-modified asphalt concrete mixtures. The material properties for the different mixtures were obtained from an FAA research project on asphalt rubber (C1) and from an FHWA study on asphalt additives (C2). The materials information obtained from these studies are presented in the following.

MATERIALS DATA FROM FAA STUDY ON ASPHALT RUBBER

The material properties for asphalt-rubber concrete mixtures determined from the FAA study were used in estimating the expected performance of rubber-modified asphalt concrete pavements. In the FAA study, a control mix consisting of AC-10 asphalt, crushed limestone, and field sand, was used as a benchmark for evaluating the expected performance of asphalt-rubber concrete mixtures. The optimum binder content for the control mix, determined using the Marshall mix design method, was found to be 4.8 percent with a target air voids content of four percent.

For the asphalt-rubber mix, the binder consisted of 77 percent AC-10 asphalt cement with three percent extender oil and 20 percent rubber. As with the control mix, the aggregates used were also crushed limestone and field sand. For both the control and asphalt-rubber mixtures, the aggregates were blended together to meet the mid-band aggregate gradation of the 1977 FAA grading specification for pavements with a bituminous surface designed to accommodate aircrafts with gross weights of 60,000 pounds or more, or with tire pressures of 100 psi or more (C3). This FAA grading band is similar to the 1990 ASTM specification for bituminous paving mixtures having a nominal maximum aggregate size of 3/8-inch that are commonly used for highway pavements carrying heavy truck traffic (C4). The FAA and ASTM grading specifications are summarized in Table C1.

The optimum binder content for the asphalt-rubber mix was 4.73 percent

Table C1. 1977 FAA Aggregate Grading Band for Bituminous Surface Course with 1/2" (12.5 mm) Maximum Particle Size.*[3]

	Percent passing (by weight)	
Sieve Size	FAA Specification	ASTM Specification
1/2 in. (12.5 mm)	100	100
3/8 in. (9.5 mm)	79-93	90-100
#4 (4.75 mm)	59-73	55-85
#8 (2.36 mm)	46-60	32-67
#16 (1.18 mm)	34-48	---
#30 (600 μm)	24-38	---
#50 (300 μm)	15-27	7-23
#100 (150 μm)	8-18	---
#200 (75 μm)	3-6	2-10

*For aircraft weighing 60,000 pounds or more or with tire pressures of 100 psi or more; compared with the 1990 ASTM aggregate grading band for bituminous paving mixtures with 3/8" (9.5 mm) nominal maximum size of aggregate.

determined using a modified Marshall mix design procedure. The air voids content was seven percent which was higher than that for the asphalt control mix (four percent). It was not possible to achieve an air voids content of four percent for the asphalt-rubber mix. This difficulty was attributed to swelling of samples after extrusion from the molds caused by a rebound action of the rubber particles. Because of this, an air voids content of seven percent was chosen as the optimum for the asphalt-rubber mix in the FAA study, with the realization that the asphalt-rubber concrete might still perform well in the testing phase and that it might compact better in the field. In addition, an air voids content of seven percent was considered to be low enough to avoid the problem of the air voids becoming interconnected producing a permeable mix that is susceptible to damage by moisture and oxidative aging.

The resilient modulus, fatigue, creep, and permanent deformation characteristics of laboratory-prepared samples of conventional and rubber-modified asphalt concrete mixtures were characterized in a comprehensive test program conducted at TTI. The different tests that were performed and the results obtained are presented in the following paragraphs.

Resilient Modulus Data

The resilient modulus, defined as the ratio of repeated axial deviator stress to the recoverable axial strain, was measured using the test procedure developed by Schmidt (C5). In this test, a 0.1-second load pulse is applied every three seconds across the vertical diameter of a cylindrical, Marshall-type specimen. The resultant deformation across the horizontal diameter is measured and the resilient modulus is calculated from the following formula:

$$M_r = \frac{P(\nu + 0.2734)}{\Delta t} \qquad (C1)$$

where

M_r = resilient modulus, psi,
P = applied load, lbs,
ν = Poisson's ratio for asphalt,
Δ = deformation across the horizontal diameter, inches, and
t = height of the specimen, inches.

Resilient moduli were determined at three different temperatures: 33°F, 77°F, and 104°F. Test results are summarized in Figure C1 which shows measured resilient moduli for the conventional and rubber-modified asphalt concrete mixtures. The data shown in Figure C1 suggest that the control mix is more temperature susceptible than the asphalt-rubber mix.

Fatigue Parameters

Beam fatigue tests were conducted to determine the fatigue parameters K_1 and K_2 of the phenomenological equation:

$$N_f = K_1 * (\frac{1}{\epsilon_t})^{K_2} \qquad (C2)$$

where

N_f = number of repetitions or load applications to failure,

ϵ_t = tensile strain, and

K_1, K_2 = fatigue parameters.

Test procedures described in the VESYS IIM User's Manual (6) were followed in the characterization of fatigue behavior. Fatigue tests were conducted under controlled stress loading at temperatures of 34°F, 68°F, and 104°. Applied loads were chosen so that specimens failed at different numbers of load repetitions. Thus, a range of data points was obtained, with each point representing a specimen that sustained an observed number of load repetitions prior to failure for a given level of initial bending strain. The initial bending strain was the strain measured in the beam at or near 200 cycles.

Through regression analysis, the fatigue parameters K_1 and K_2 for the conventional and rubber-modified asphalt concrete mixtures were determined for the three different test temperatures. Table C2 shows the calculated fatigue parameters while Figures C2 through C4 illustrate the fatigue relationships obtained. It is observed from the figures that laboratory fatigue life is generally improved with the addition of rubber in the mix.

The fatigue constants K_1 and K_2 shown in Table C2 were used to establish regression equations for these parameters as a function of temperature. The

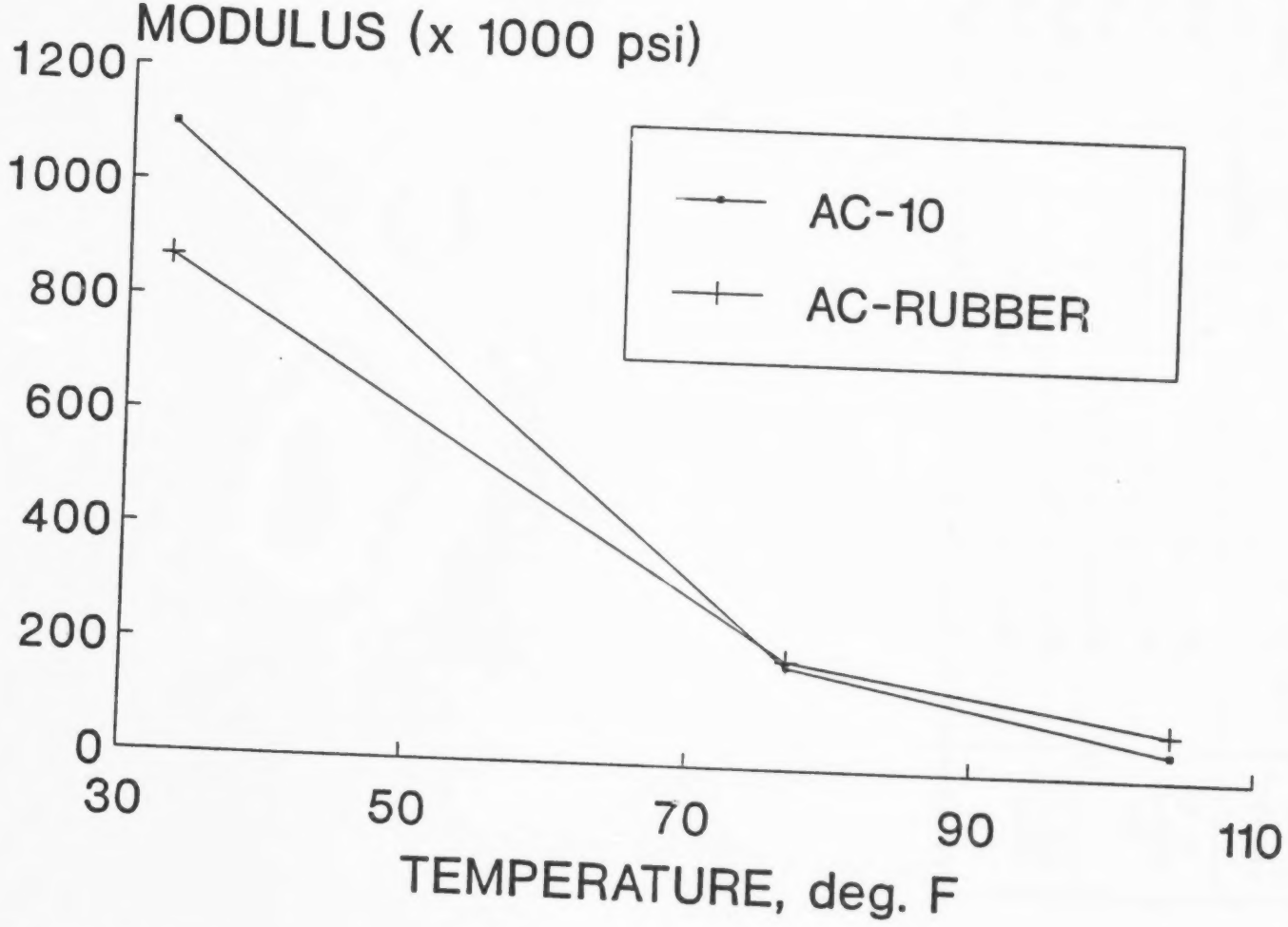


Figure C1. Variation of Diametral Resilient Modulus with Temperature for AC-10 and Rubber-Modified Asphalt Mixtures.

Table C2. Fatigue Parameters K_1 and K_2 from Laboratory Fatigue Tests on AC-10 and Asphalt - Rubber Concrete Mixtures.

Material	Temperature, °F	K_1	K_2	Number of Samples	Correlation Coefficient, R
AC-10 Control Mix	104	3.21×10^{-3}	2.35	8	-0.89
	68	9.48×10^{-12}	4.69	8	-0.95
	34	1.43×10^{-6}	2.92	7	-0.63
Asphalt-Rubber	104	2.82×10^{-6}	3.47	10	-0.85
	68	3.16×10^{-5}	2.82	9	-0.98
	34	9.91×10^{-10}	4.04	9	-0.86

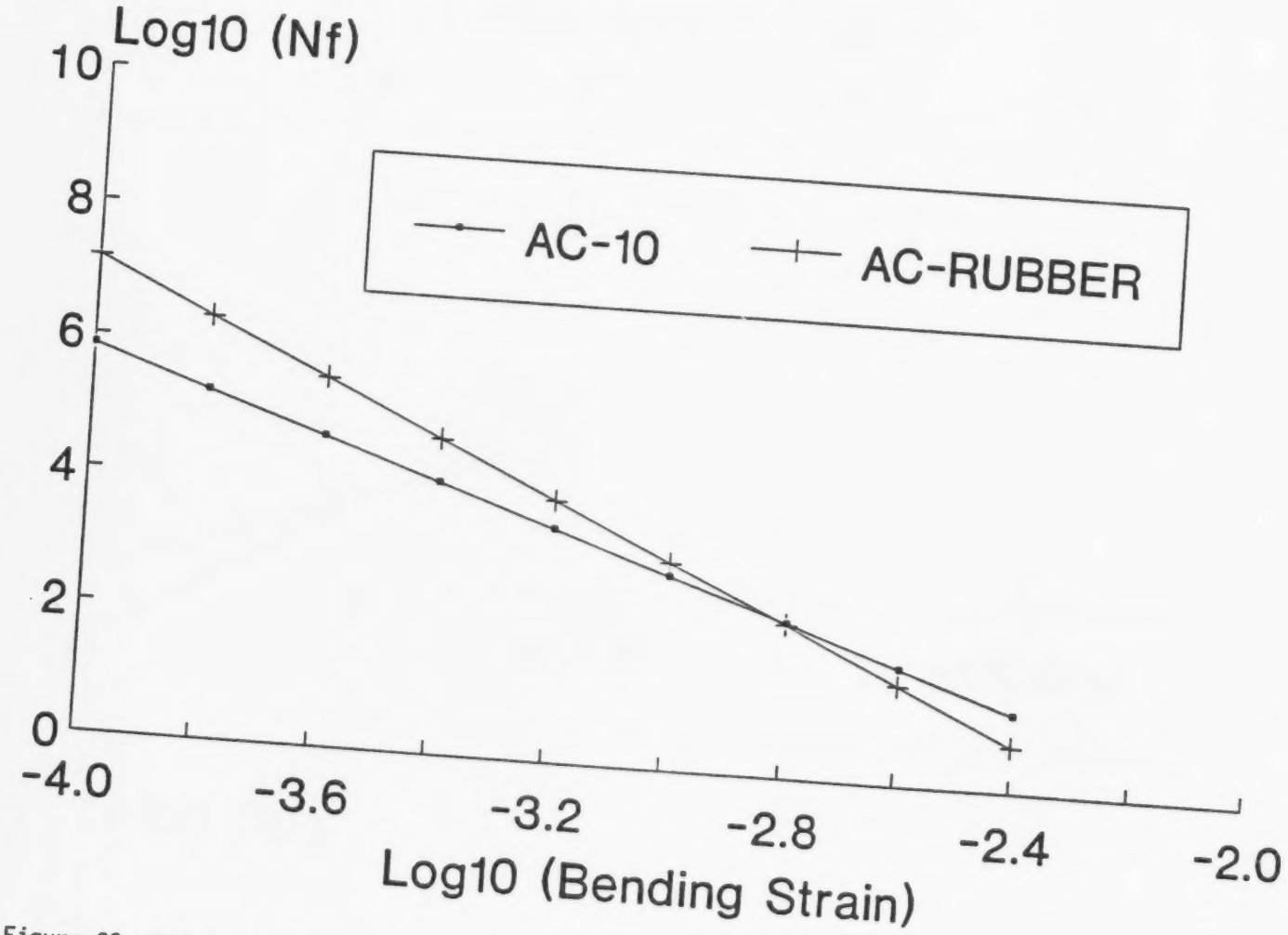


Figure C2. Fatigue Relationship at 34°F for AC-10 and Rubber-Modified Asphalt Mixtures.

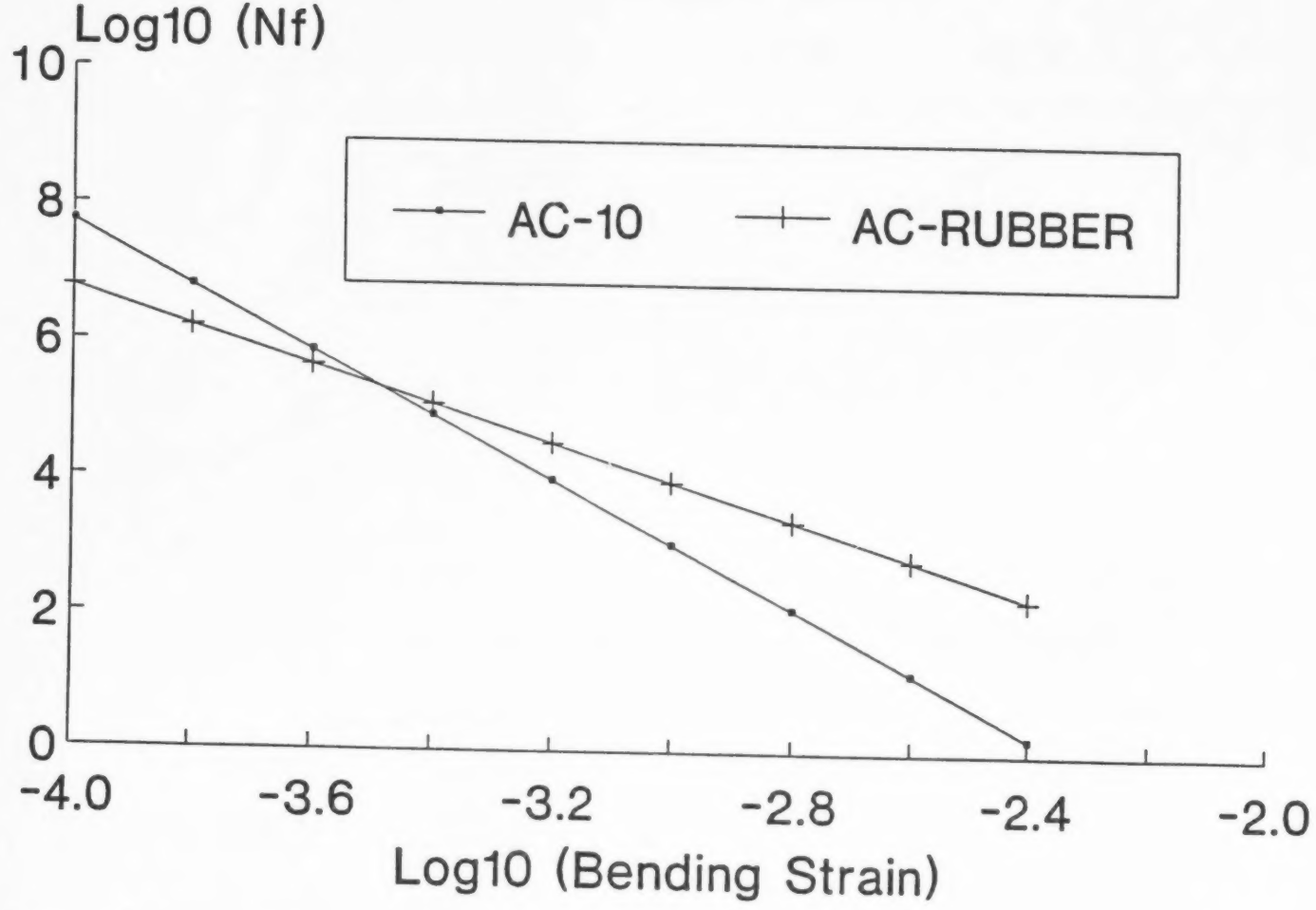


Figure C3. Fatigue Relationships at 68°F for AC-10 and Rubber-Modified Asphalt Mixtures.

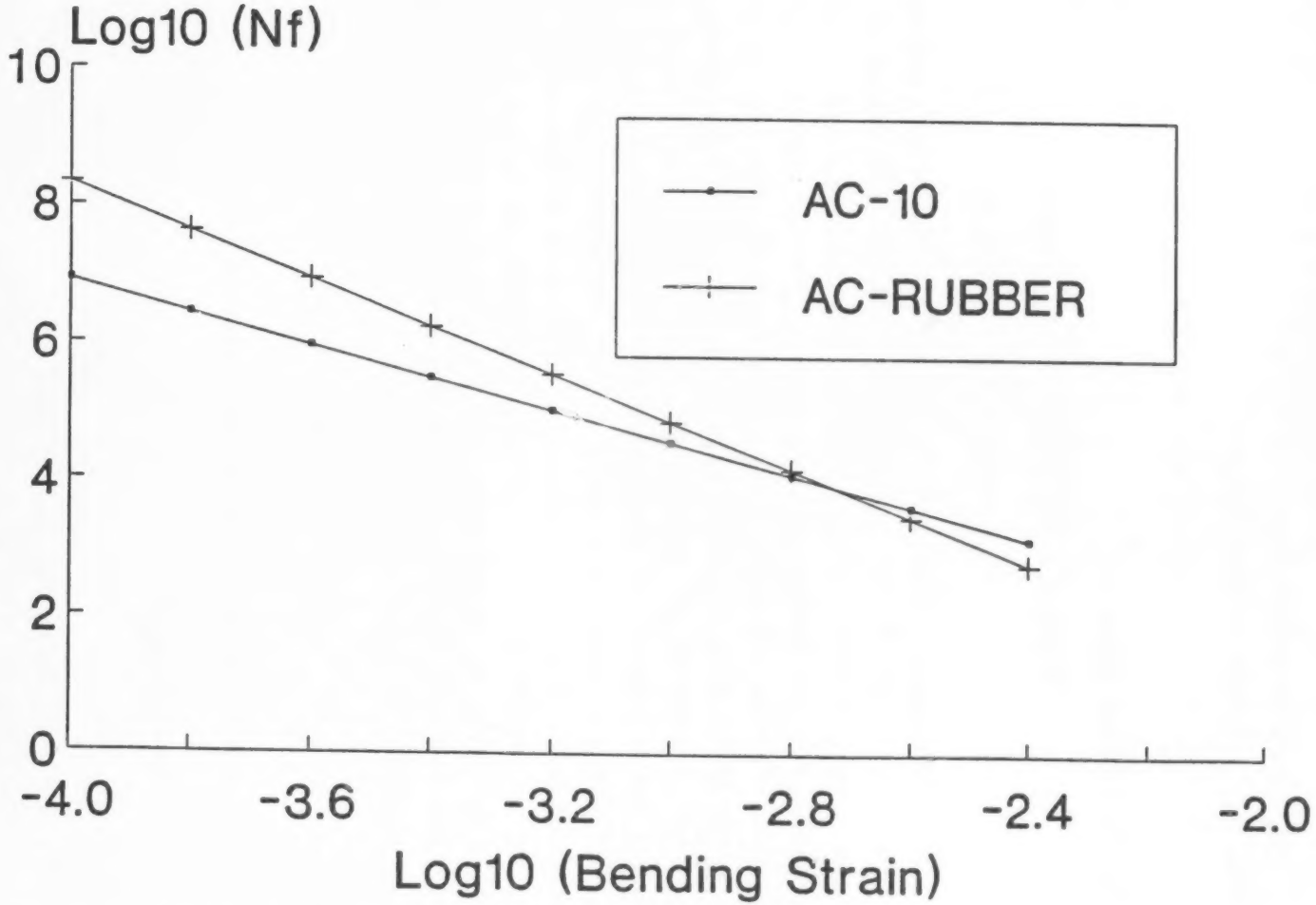


Figure C4. Fatigue Relationships at 104°F for AC-10 and Rubber-Modified Asphalt Mixtures.

regression equations obtained are given by the following:

For the AC-10 control mix:

$$|\log_{10} K_1| = 14.630 - 4.558 \log_{10} T \quad \text{(C3)}$$

$$K_2 = 1.512 - 0.280 \log_{10} K_1 \quad \text{(C4)}$$

For the asphalt-rubber mix:

$$|\log_{10} K_1| = 20.483 - 7.879 \log_{10} T \quad \text{(C5)}$$

$$K_2 = 1.900 - 0.243 \log_{10} K_1 \quad \text{(C6)}$$

For each seasonal temperature, T, the above equations were used to predict the constants K_1 and K_2 for evaluating the fatigue performance of the FAA mixtures. The predicted laboratory fatigue constants are given in Table C3.

In general, the fatigue constants determined in the laboratory will underestimate the fatigue life in the field. A laboratory fatigue test is, after all, just an approximation of the actual phenomenon that occurs in the field, and such factors as the healing of the pavement between load applications, residual stresses, and variability in the position of the wheel load are not accounted for. Consequently, researchers have used shift factors to adjust the laboratory fatigue constants to more realistically predict field fatigue life.

For the performance evaluation reported herein, the fatigue constants were adjusted following the methodology developed by Lytton and Tseng (C7). These researchers have proposed the following equations for shifting the laboratory fatigue constants to values representative of field conditions:

$$SF = SF_r * SF_h \quad \text{(C7)}$$

where

SF_r = shift factor due to residual stresses,

$$= \left(\frac{1}{[1 - p_0 t^{-m}]}\right)^{K_{21}} \quad \text{(C8)}$$

SF_h = shift factor due to healing,

$$= 1 + 5.923 \times 10^{-6} n_i (t_i)^{0.427} \quad \text{(C9)}$$

Table C3. Fatigue Constants K_1 and K_2 for AC-10 and Asphalt-Rubber Concrete Mixtures.

		K_1		K_2	
Material	Temperature, °F	Laboratory	Field	Laboratory	Field
AC-10 Control Mix	35	2.56×10^{-8}	5.436×10^{-8}	3.64	3.5660
	65	4.30×10^{-7}	8.411×10^{-7}	3.29	3.2255
	95	2.42×10^{-6}	7.098×10^{-6}	3.08	2.9780
	60	2.99×10^{-7}	5.787×10^{-7}	3.34	3.2762
Asphalt Rubber	35	4.81×10^{-9}	1.711×10^{-8}	3.92	3.7916
	65	6.32×10^{-7}	1.848×10^{-6}	3.41	3.3019
	95	1.26×10^{-5}	3.741×10^{-5}	3.09	2.9810
	60	3.36×10^{-7}	9.704×10^{-7}	3.47	3.3633

K_{2i} = laboratory determined value for K_2,

p_o = percent of total strain remaining in the pavement as residual strain immediately after the passage of a wheel load,

m = exponential relaxation rate,

t = time, and

n_{ri} = number of rest periods of length t_i.

It may be observed that the shift factor is made up of two components: an adjustment factor due to residual stresses, and an adjustment factor due to healing during rest periods. The first component accounts for the build-up of residual stresses in the asphalt layer with cumulative load applications. These residual stresses, which may be compressive or tensile, remain at the bottom of the asphalt layer after the passage of each load. The effect of these stresses is thus to "prestress" the layer so that the tensile stresses that occur during the passage of the next wheel load cause much less (or much more) fatigue damage depending upon whether the asphalt layer accumulates more (or less) residual stress than the base course layer beneath it. Yandell and Lytton (C8, C9), in their study of residual stresses in a pavement, have found that, due to residual compressive or tensile strain, the tensile stress resulting from a wheel load application is approximately between 80 and 120 percent of the strain resulting from the preceding wheel load. Thus, p_o, in Eq. (C8), ranges approximately from +20 to -20 percent. For the performance evaluation discussed herein, p_o, in Eq. (C8), was assumed to have a value of 0.20. In addition, the slope, m, of the creep compliance curve, determined from compressive creep tests, was used to estimate the exponential relaxation rate. The compressive creep parameters are presented in the subsequent section.

The second component of the shift factor, given previously, accounts for the healing that takes place in the field between load applications. In this process, the microcracks in the material beyond the visible cracks undergo healing, partly because of the viscoelastic recovery of the asphalt cement, and partly because of the reformation of bond forces in the material after the passage of a wheel load. The expression for the shift factor given by Eq. (C9) is based on data from the TTI overlay tester, and on work conducted by Balbissi

(C10). The equation indicates an increasing shift factor due to healing as the length of the rest period is increased. Thus, for pavements with a high traffic rate, the rest period is short, and the predicted shift factor would be small. Conversely, for pavements with a low traffic rate, the rest period is longer, and the predicted shift factor would be larger.

The above methodology for shifting the laboratory fatigue constants is currently incorporated in the FLEXPASS computer program. The adjusted fatigue constants, determined from application of the methodology, are also summarized in Table C3.

Creep Data

Compressive creep tests were conducted on cylindrical specimens four inches in diameter and eight inches high at test temperatures of 40°F, 70°F, and 100°F. Three replicate samples for each type of mix were tested at each temperature and the averages of the compliances measured were fitted to a curve of the form:

$$D(t) = D_1 * t^m \qquad (C10)$$

where

D(t) = creep compliance at time t, defined as the ratio of measured strain at time t to the applied constant stress

and

D_1, m = equation parameters.

The compressive creep parameters determined are summarized in Table C4.

The compressive creep test is an extremely useful test to perform since the creep parameters are related to several important properties including permanent deformation, temperature susceptibility, and fracture properties. Lytton (C1), for instance, derived relationships between the permanent deformation parameters, μ and α, in the VESYS equation for permanent strain, and the compressive creep parameters of Eq. (C10) above. The permanent strain at each load cycle, expressed as a percentage of the resilient strain, is modeled in the VESYS program by the following equation:

$$F(N) = \mu * N^{-\alpha} \qquad (C11)$$

Table C4. Creep Compliance Parameters for AC-10 and Asphalt-Rubber Concrete Mixtures.[1]

Material	Temperature °F	D_1	m
AC - 10 Control Mix	40	1.38×10^{-6}	0.354
	70	7.91×10^{-6}	0.254
	100	1.83×10^{-5}	0.128
Asphalt Rubber	40	1.70×10^{-6}	0.289
	70	9.20×10^{-6}	0.211
	100	1.42×10^{-5}	0.164

where

F(N) = fraction of the resilient strain that remains as permanent strain at a given load cycle,

N = cumulative load cycles, and

μ, α = permanent deformation parameters.

Lytton found that the parameter α is equal to (1-m) and that μ is a function of the parameters of both the creep and recovery curves.

In addition to permanent deformation properties, the creep compliance characteristics are also related to the fracture properties of asphalt concrete materials. The fracture of asphaltic concrete is modeled by the Paris and Erdogan equation (C11):

$$\frac{dc}{dN} = A^*(\Delta K)^n \tag{C12}$$

where

$\frac{dc}{dN}$ = rate of crack growth,

ΔK = change in the stress intensity factor with each load cycle, and

A, n = fracture parameters.

In a landmark development, Schapery (C12) derived explicit relationships for the fracture parameters A and n which were functions of, among other things, the creep compliance characteristics and the tensile strength. For instance, the exponent n in Eq. (C12) is determined simply as:

$$n = \frac{2}{m_t} \tag{C13}$$

where m_t is the slope of the tensile log creep compliance versus log time curve.

Although tensile creep compliance tests were not performed in the FAA study, Hoyt et al. estimated the tensile fracture exponent n from the slope m of

the compressive creep compliance curve and the volumetric concentration of the binder. The estimated tensile fracture exponents are summarized in Table C5. In this table, the compressive fracture exponent n_c for a given mix at a certain temperature was determined from Eq. (C13) using the measured value of the slope m of the compressive creep curve. Following the rule of mixtures, the calculated values of n_c were then multiplied by the volumetric concentration of the binder for a given mix to get estimates of the tensile fracture exponents at different temperatures.

Repeated-Load Permanent Deformation Data

Permanent deformation characteristics of conventional and asphalt-rubber concrete mixtures under repeated loading were also determined in the FAA study. The increase in permanent strain with cumulative load cycles was modeled using a nonlinear, three-parameter model of the form:

$$\epsilon_a = \epsilon_0 * \exp[-(\frac{\rho}{N})^{\beta}] \qquad (C14)$$

where

ϵ_a = permanent strain,

N = cumulative load cycles, and

ϵ_0, ρ, β = permanent deformation parameters.

The permanent deformation parameters determined for each mix at test temperatures of 40°F, 70°F, and 100°F are summarized in Table C6. These parameters are used in predicting the amount of rutting that will occur in asphalt concrete pavements. For a single axle load, Tseng and Lytton (C13) derived the following relationship for rutting as a function of the parameters ϵ_0, ρ, and β:

$$\delta_a(N) = \sum_{i=1}^{n} (\frac{\epsilon_{0i}}{\epsilon_{ri}}) \exp[-(\frac{\rho_i}{N})^{\beta i}] \int_{d_{i-1}}^{d_i} \epsilon_{ci}(z)\, dz \qquad (C15)$$

Table C5. Estimated Fracture Exponents for AC-10 and Asphalt-Rubber Concrete Mixtures.[1]

Material	Temperature, °F (°C)	Compressive Compliance Slope, m	Compressive Fracture Exponent $n_c = \frac{2}{m}$	Volumetric Concentration of Binder C_b	Estimated Tensile Fracture Exponent n
AC-10 Control	40 (4.4)	0.354	5.65		0.667
	70 (21.1)	0.254	7.87	0.118	0.929
	100 (37.8)	0.128	15.63		1.844
AR-Medium	40 (4.4)	0.289	6.92		0.817
	70 (21.1)	0.211	9.48	0.118	1.119
	100 (37.8)	0.164	12.20		1,440

Table C6. Permanent Deformation Parameters for AC-10 and Asphalt-Rubber Concrete Mixtures.[1]

Material	Temperature °F	ϵ_0	ρ	B	ϵ_0 / ϵ_r
AC -10 Control Mix	40	0.0187	1.1539×10^{16}	0.0637	1,662
	70	0.0008	0.9817×10^{4}	0.2070	27.44
	100	0.9355	6.3750×10^{16}	0.0591	31,509
Asphalt - Rubber	40	0.0181	3.4514×10^{16}	0.0645	1,445
	70	0.0238	2.8904×10^{16}	0.0524	544
	100	0.0588	2.5023×10^{16}	0.0560	1,680

where

$\delta_a(N)$ = permanent deformation at load cycle N,

n = number of pavement layers,

ϵ_{ri} = measured resilient strain in the laboratory for the material in the i^{th} layer,

ϵ_{ci} = compressive strain in the i^{th} layer under load, and

d_i = depth of the i^{th} layer.

MATERIALS DATA FROM FHWA STUDY ON ASPHALT ADDITIVES

Little et al. (C2) evaluated conventional and additive-modified asphalt concrete mixtures in a study conducted at TTI for FHWA. The following different types of additives were investigated: 1) Carbon black; 2) thermoplastic block copolymer (Kraton); 3) polyethylene finely dispersed in asphalt (Novophalt); and 4) copolymers of ethylene and vinyl acetate (Elvax). Two different aggregates and asphalts from two different sources were used in preparing mixtures for evaluation. The aggregate used in most of the laboratory tests consisted of sub-rounded siliceous river gravel and similar sand with limestone crusher fines added to improve stability. This material was selected as the primary aggregate because it produces a relatively binder-sensitive mixture which accentuates the differences between binders more so than a high-stability mix. The secondary aggregate was composed of crushed limestone with field sand added to improve workability.

The asphalts came from the Texaco refinery in Port Neches, Texas, and from a refinery in San Joaquin Valley, California. Since repeated-load permanent deformation data for evaluating pavement rutting was only available for mixtures with the San Joaquin Valley asphalt, the performance evaluation of additive-modified asphalt concrete mixtures was limited herein to San Joaquin Valley asphalt mixes. For these mixtures, the primary aggregate consisting of siliceous river gravel, sand, and limestone crusher fines was used. Optimum binder contents for the different additive-modified asphalt concrete mixtures were determined using the Marshall mix design method. For most mixtures, the optimum binder content was found to be about 4.5 percent. In addition, the amount of additive used was five percent by weight of the asphalt cement, except for carbon

black for which 15 percent was used. Results from the Marshall mix design are summarized in Table C7.

Resilient modulus, fracture, and repeated-load permanent deformation tests were conducted on samples made of the San Joaquin Valley asphalt. The properties obtained, which were used for evaluating the expected performance of additive-modified asphalt concrete mixtures, are presented in the following information.

Resilient Modulus

Resilient modulus was measured at temperatures of -10°F, 32°F, 68°F, 77°F, and 104°F using the test procedure developed by Schmidt. The moduli determined are summarized in Figure C5 for the different mixtures of California Valley asphalt that were evaluated.

Fracture Properties

Fracture properties were evaluated using the TTI "overlay tester". A schematic diagram of this device is shown in Figure C6. The device applies a repeated controlled displacement to a test sample fastened to two platens at the bottom of the tester. One platen is free to move, while the other platen is fixed. The test specimen is placed above the joint between the two platens and a cyclic force, P, is applied on the movable platen to open and close an initial crack simulated by a notch on the test specimen. The maximum opening is pre-set, and the movement of the joint is continuously monitored using Linear Variable Differential Transformers. The cyclic load, P, is measured by a load cell. Repeated opening and closing of the joint causes the crack to propagate upward until it eventually reaches the top of the specimen at which time the test is terminated.

Figure C7 illustrates a typical plot of load versus crack opening obtained from the overlay tester. The load-displacement loops for two successive cycles are illustrated in the figure. The area within the load-displacement loop for a given cycle is the work required to extend the crack through the sample. The difference in the areas, indicated by the shaded region in Figure C, is the energy dissipation as the crack grows from cycle N to cycle N+1. This difference, divided by the change in crack length, is a measure of the J-integral used in fracture theory.

Table C7. Marshall Mix Design Data for San Joaquin Valley Asphalt Concrete Mixtures.[2]

Material	% Asphalt Content	% Air Voids Content	Marshall Stability, lbs.	Marshall Flow	% VMA
AC-20 (Control)	4.6	5.0	1,200	7	12
AC-5 + 15% Carbon Black	4.7	7.1	1,000	6	14
AC-5 + 5% Kraton	4.5	5.0	900	6	13
AC-5 + 5% Novophalt	4.5	4.7	1,100	6	12
AC-5 + 5% Elvax	4.5	5.2	700	7	13

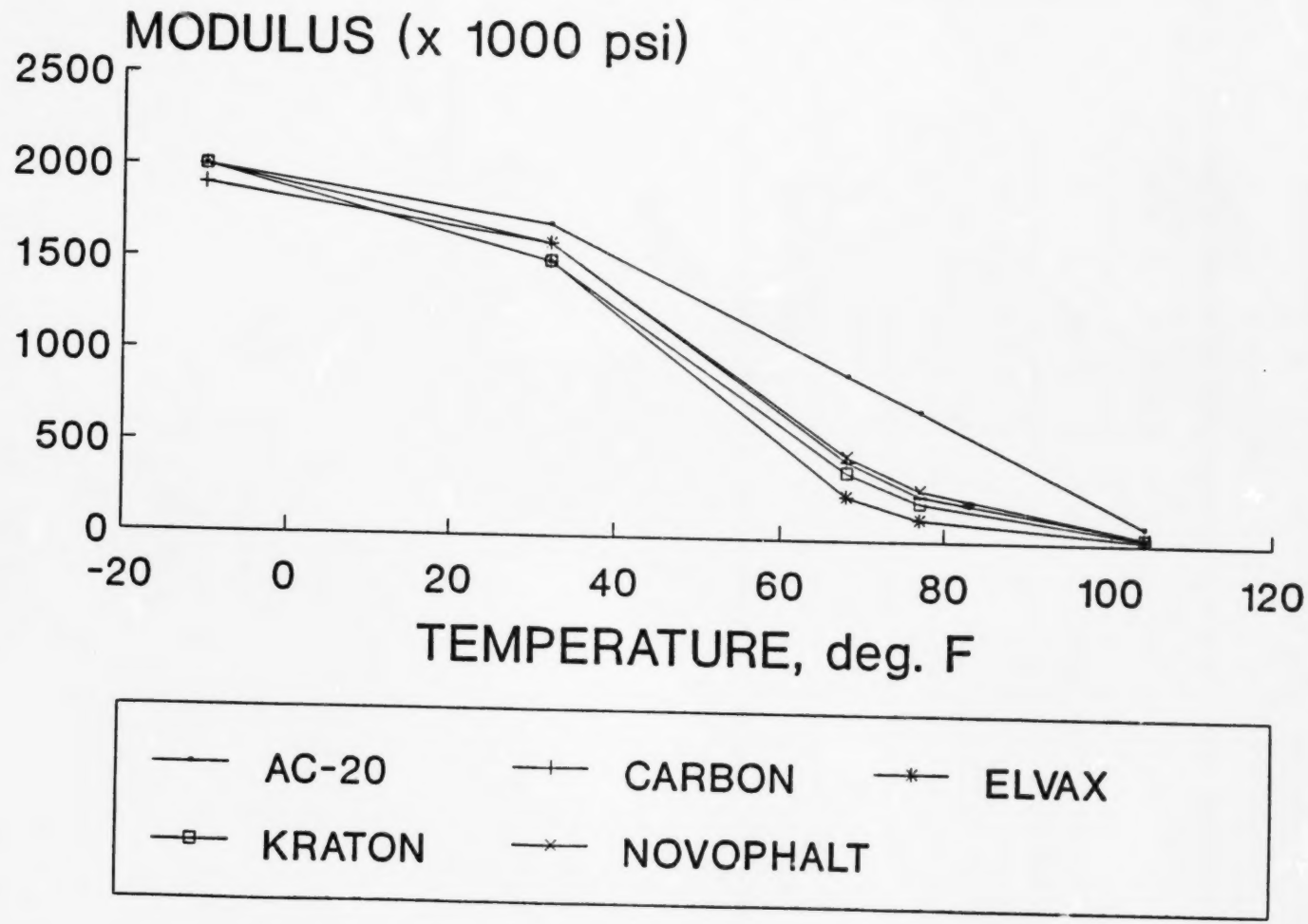


Figure C5. Variation of Diametral Resilient Modulus with Temperature for San Joaquin Valley Asphalt Mixtures.

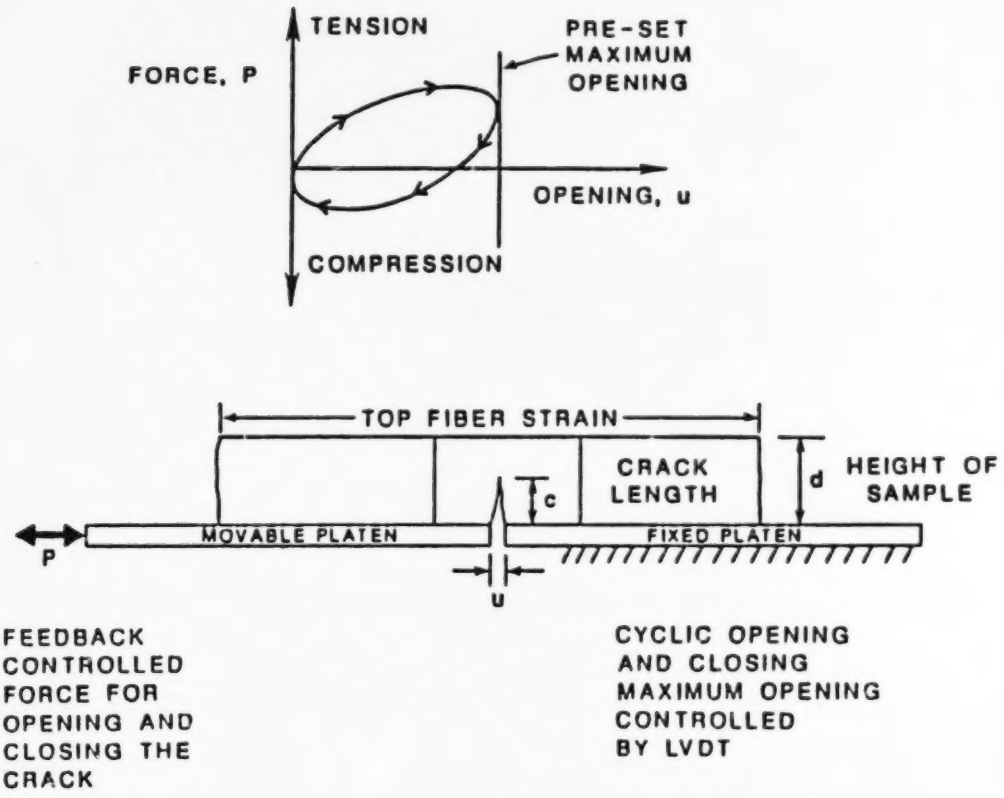


Figure C6. Schematic Diagram of Overlay Tester.

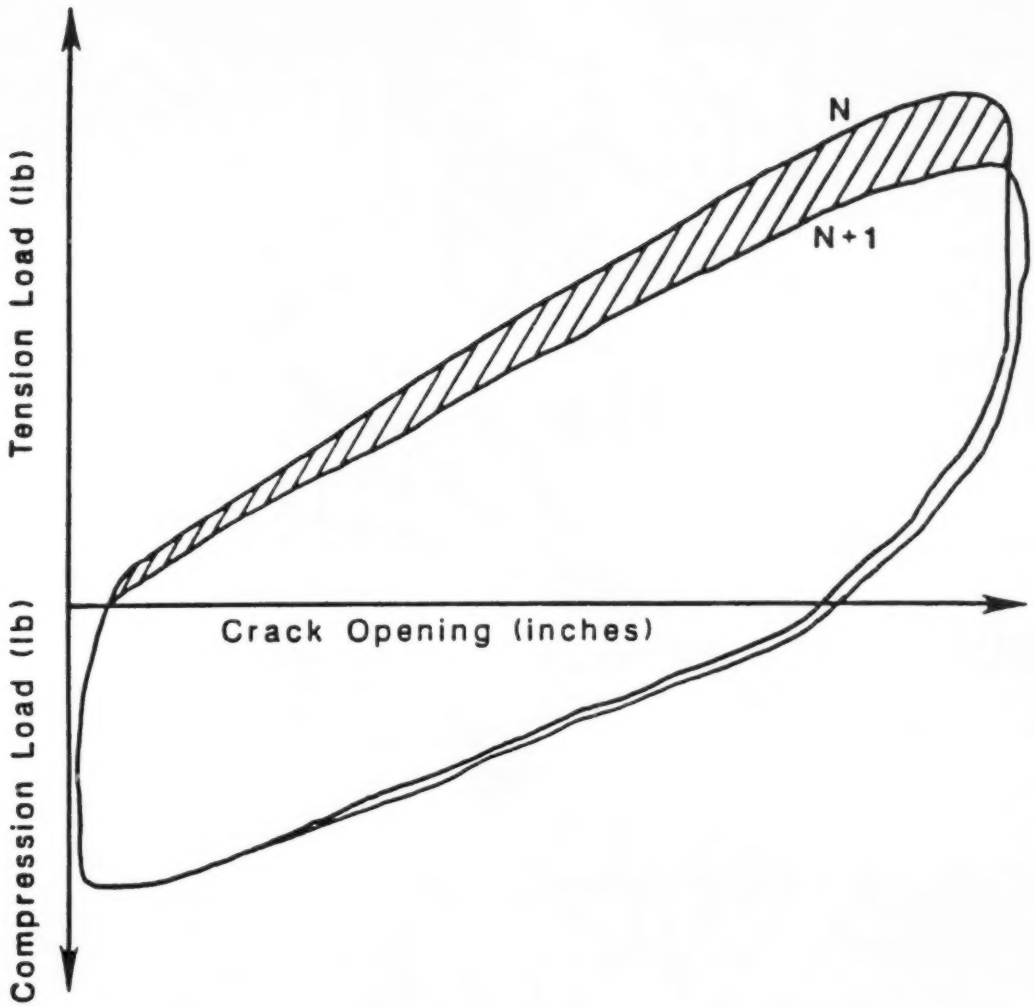


Figure C7. Typical Recording of Load Versus Crack Opening from Overlay Tester.

The data from the fracture tests were fitted to a model having the same form of the Paris and Erdogan equation. Specifically, the rate of crack growth was related to the J-integral using the equation:

$$\frac{dc}{dN} = A^{\bullet} (J^{\bullet})^{n^{\bullet}} \tag{C16}$$

The measured values of $A^{\bullet}$ and $n^{\bullet}$ for the samples tested are summarized in Table C8. For linear elastic and linear viscoelastic materials, the J-integral is related to the stress-intensity factor K by the equation:

$$J = K^2 \frac{(1 - \nu^2)}{E} \tag{C17}$$

where

ν = Poisson's ratio and

E = modulus.

By substituting Eq. (C17) into Eq. (C16), the parameters A and n of the Paris and Erdogan equation may be estimated from the measured values of $A^{\bullet}$ and $n^{\bullet}$ as follows:

$$\frac{dc}{dN} = A^{\bullet}[(\frac{1 - \nu^2}{E}]^{n^{\bullet}} (K^{2n^{\bullet}}) \tag{C18}$$

Thus,

$$A = A^{\bullet}[\frac{(1 - \nu^2)}{E}]^{n^{\bullet}} \tag{C19}$$

$$n = 2n^{\bullet} \tag{C20}$$

The computed values of A and n from Eqs. (C19) and (C20) may then be used in estimating the fatigue parameters K_1 and K_2 from the following theoretical relationships developed by Tseng and Lytton (C7):

Table C8. Average Measured Fracture Parameters A* and N* for San Joaquin Valley Asphalt Concrete Mixtures.[2]

Material	33°F		77°F	
	A*	N*	A*	N*
AC-20 (Control Mix)	---	---	0.006599	0.833
AC-5 + 15% Carbon Black	0.036138	0.93933	0.002664	1.4285
AC-5 + 5% Kraton	0.014938	0.941	0.001375	2.0315
AC-5 + 5% Novophalt	0.017123	1.630	0.001424	1.767
AC-5 + 5% Elvax	0.007861	0.827	0.001223	1.9225

$$K_1 = \frac{(d^{1-\frac{n}{2}})\,[1-(\frac{C_0}{d})^{1-nq}]}{[A(1-nq)\ \ (rE)^n]} \qquad \text{(C21)}$$

$$K_2 = n \qquad \text{(C22)}$$

where

d = thickness of the sample,

C_0 = radius of the maximum-sized aggregate in the mix,

A, n = fracture parameters of the Paris and Erdogan equation,

E = modulus, and

r, q = constants that relate the stress-intensity factor to the geometry of the sample, the loading, and the crack length.

From finite element analysis, r and q were found to have values of 4.3974 and 1.1798 respectively.

Since flexural beam fatigue tests were not run on mixtures made of San Joaquin Valley asphalt in the FHWA study, Eqs. (C19) through (C22) were used to estimate the fatigue parameters K_1 and K_2 from the measured fracture properties. The predicted laboratory fatigue constants are summarized in Table C9. Shift factors were also applied to the laboratory fatigue constants following the procedure developed by Tseng and Lytton presented in an earlier section. The shifted fatigue constants, which are considered to be representative of field conditions, are also summarized in Table C9.

Creep Data

Compressive creep compliance tests were performed on samples of San Joaquin Valley asphalt concrete mixes at 70° F. The creep parameters D_1 and m, obtained by fitting Eq. (C10) to the measured test data, are summarized in Table C10.

Repeated-Load Permanent Deformation Data

The permanent deformation behavior of additive-modified mixtures were also evaluated in the FHWA study. Repeated-load tests were conducted on cylindrical samples, 4 inches in diameter and 8 inches high, at 70° F. Using nonlinear regression, the test data were fitted to the three-parameter permanent

Table C9. Fatigue Constants K_1 and K_2 at 70°F for San Joaquin Valley and Rubber-Modified Asphalt Concrete Mixtures.

Material	K_1		K_2	
	Laboratory	Field	Laboratory	Field
AC-20 Control Mix	1.61×10^{-3}	2.057×10^{-3}	1.7660	1.7494
AC-5 + 15% Carbon Black	7.92×10^{-6}	1.503×10^{-5}	2.7014	2.6461
AC-5 + 5% Kraton	6.12×10^{-6}	1.988×10^{-7}	3.7160	3.5950
AC-5 + 5% Novophalt	1.37×10^{-7}	3.312×10^{-7}	3.4904	3.4033
AC-5 + 5% Elvax	3.55×10^{-7}	7.657×10^{-7}	3.4964	3.4183
Asphalt-Rubber	1.13×10^{-6}	4.618×10^{-6}	3.345	3.2032

Table C10. Creep Compliance Properties of San Joaquin Valley Asphalt Mixtures at 70°F.

Material	D_1	m
AC-20 Control Mix	4.622×10^{-6}	0.452
AC-5 + 15% Carbon Black	1.335×10^{-5}	0.263
AC-5 + 15% Kraton	1.894×10^{-5}	0.307
AC-5 + 5% Novophalt	1.355×10^{-5}	0.344
AC-5 + 5% Elvax	6.748×10^{-6}	0.414

deformation model given by Eq. (C14). The resulting parameters ϵ_0, ρ, and β determined for each mixture are given in Table C11. These data were used to predict the rutting performance of the different additive-modified mixtures considered.

Table C11. Permanent Deformation Parameters at 70°F for San Joaquin Valley Asphalt Concrete Mixtures.

Material	ϵ_0	ρ	β
AC-20 (Control Mix)	0.000392	0.242035×10^{3}	0.2948
AC-5 + 15% Carbon Black	0.001100	0.108695×10^{5}	0.1300
AC-5 + 15% Kraton	0.160350	1.93295×10^{16}	0.0500
AC-5 + 5% Novophalt	0.000258	0.234333×10^{2}	0.4579
AC-5 + 5% Elvax	0.000652	0.108765×10^{4}	0.1700

REFERENCES

C1. Hoyt, D. M., Lytton, R. L., and Roberts, F. L., "Criteria for Asphalt-Rubber Concrete in Civil Airport Pavements: Vol II - Evaluation of Asphalt-Rubber Concrete," Report No. DOT/FAA/PM-86/39, II, Federal Aviation Administration, Washington, D. C., 1987.

C2. Little, D. N., Button, J. W., White, R. M., Ensley, E. K., Kim, Y., and Ahmed, S. J., "Investigation of Asphalt Additives," Report No. FHWA/RD-87/001, Federal Highway Administration, McLean, Virginia, 1986.

C3. "Bituminous Surface Course," Standards for Specifying Construction of Airports - New Standard for Plant Mix Bituminous Materials, Advisory Circular No. 150/5370-10, Item P-401, Federal Aviation Administration, Washington, D. C., 1977.

C4. "Standard Specification for Hot-Mix, Hot-Laid Bituminous Paving Mixtures," 1990 Annual Book of ASTM Standards, Designation D 3515-89, Vol. 04.03, American Society for Testing and Materials, Philadelphia, Pennsylvania, 1990.

C5. Schmidt, R. J., "A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes," Highway Research Record No. 404, Highway Research Board, Washington, D. C., 1972, pp. 23-32.

C6. Kenis, W. J., "Predictive Design Procedures, VESYS User's Manual - An Interim Design Method for Flexible Pavement Using the VESYS Structural Subsystem," Final Report No. FHWA-RD-77-154, Federal Highway Administration, McLean, Virginia, 1978.

C7. Tseng, K., and Lytton, R. L., "Fatigue Damage Properties of Asphaltic Concrete Pavements," paper presented at the 69th Annual Meeting of the Transportation Research Board, Washington, D. C., 1990.

C8. Yandell, W. O., and Lytton, R. L., "Residual Stresses Due to Traveling Loads and Reflection Cracking," Report No. FHWA/TX-79-207-6, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1979.

C9. Yandell, W. O., and Lytton, R. L., "The Effect of Residual Stress and Strain Build-Up in a Flexible Pavement by Repeated Rolling of a Tire," Report RF4087-1, Texas Transportation Institute, Texas A&M University, College Station, Texas, 1979.

C10. Balbissi, A. H., "A Comparative Analysis of the Fracture and Fatigue Properties of Asphalt Concrete and Sulphlex," PhD. Dissertation, Texas A&M University, College Station, Texas, 1983.

C11. Paris, P. C., and Erdogan, F., "A Critical Analysis of Crack Propagation Laws," Transactions of the ASME, Journal of Basic Engineering, Series D, Vol. 85, No. 3, 1963.

C12. Schapery, R. A., "A Theory of Crack Growth in Viscoelastic Med'a," Technical Report No., MM 2764-73-1, Mechanics and Materials Research Center, Texas A&M University, College Station, Texas, 1973.

C13. Tseng, K., and Lytton, R. L., "Prediction of Permanent Deformation in Flexible Pavement Materials," paper presented at the ASTM Symposium on Implication of Aggregates in the Design, Construction, and Performance of Flexible Pavements, New Orleans, Louisiana, 1986.